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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD ADVISORY REPORT 330

Anthropomorphic Dummies for Crash and Escape System Testing

(Mannequins anthropométriques utilisés lors des tests d'impact et d'éjection)

This Advisory Report is sponsored by the Aerospace Medical Panel of AGARD.

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North Atlantic Treaty Organization
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Anthropomorphic Dummies for Crash and Escape System Testing

(AGARD AR-330)

Executive Summary

The Aerospace Medical Panel (AMP) of the Advisory Group for Aerospace Research and Development (AGARD) convened Working Group 21: Anthropomorphic Dummies for Crash and Escape System Testing, to review the status and direction of the technology of aircraft ejection and automotive crash test dummies that will enhance future aerospace capabilities for reducing aircrew injury risk. Topics discussed included:

- a historical review of the important dummies developed in NATO countries for occupant protection in both road vehicle crashes and aircraft ejection;
- human biomechanical response requirements; i.e., the properties required of dummies to give human-like responses with which to assess injury risk;
- pertinent dimensions and masses for current adult dummies;
- injury tolerance levels for impact exposures and spinal injury levels for ejection seat assessment;
- dummy instrumentation and data acquisition systems, sensors and standards;
- new developments and special features in dummies for improved occupant protection;
- data bases and computer models for simulating occupant protection;
- organizations within NATO that use and maintain dummies for defense-oriented crash and escape system testing and evaluation.

The outcome of Working Group 21 is this Advisory Report which addresses these issues and recommends that, to improve performance evaluation and safety assessment of aircrew escape and crash protective systems, AGARD/AMP must promote within the aerospace community:

- the need for aircraft systems-effectiveness testing to include an injury potential assessment based on measurements made within a dummy for different operational injuries, as is commonly done in automotive testing;
- the need for developing a family of dummy sizes to include the entire flying population, including female aircrew;
- the need for developing enhanced instrumentation, including seat-mounted acceleration recorders, reliable angular accelerometers, dummy on-board data acquisition and processing systems, etc., to improve injury assessment and aid in dummy data handling;
- the need of affordability for initial acquisition, use and maintenance of dummies;
- the exploitation of validated computer models as human surrogates to reduce the requirements for impact and ejection system testing.

Mannequins anthropométriques utilisés lors des test d'impact et d'éjection

(AGARD AR-330)

Synthèse

Le Panel de médecine aérospatiale du Groupe consultatif pour la recherche et les réalisations aérospatiales (AGARD) a convoqué le Groupe de travail No. 21 sur: “Les mannequins anthropomorphiques pour la mise au point des moyens d'essais pour les crashs et les systèmes d'évacuation”, ceci afin de faire le point de l'état des connaissances et des orientations prises pour les technologies d'éjection à partir des aéronefs et les essais automobiles sur mannequins lors des crashs, l'objectif étant d'identifier les principales recherches sur les mannequins qui seront susceptibles de réduire les risques de blessure courus par les équipages à l'avenir. Les sujets suivants ont été examinés:

- une revue historique des principaux mannequins développés dans les pays membres de l'OTAN pour la protection des occupants en cas d'accidents de la circulation, ainsi que lors de l'éjection en vol;
- la spécification des réponses biomécaniques humaines c'est à dire les caractéristiques des mannequins souhaitées afin d'assurer des réponses quasi-humaines permettant d'évaluer les risques de blessures;
- les dimensions et les masses pertinentes, pour les mannequins de taille adulte actuels;
- les degrés de tolérance aux blessures pour l'exposition aux impacts et les niveaux de gravité de lésions de la colonne vertébrale pour l'évaluation des sièges éjectables;
- de l'instrumentation, des systèmes acquisition de données, des senseurs et des normes pour mannequins;
- de nouveaux développements et des caractéristiques spéciales pour les mannequins, afin d'assurer une meilleure protection pour les occupants;
- des bases de données et des modèles informatiques pour la simulation de la protection des occupants;
- les organismes au sein de l'OTAN qui utilisent et assurent la maintenance des mannequins demandés pour les essais et l'évaluation des systèmes d'essais de crashs et d'évacuation orientés défense.

Ce rapport consultatif est le résultat des travaux du Groupe de travail No. 21. Il examine les questions évoquées ci-dessus et recommande que, pour améliorer l'évaluation des performances et de la sécurité des systèmes de protection et d'évacuation des équipages et des systèmes de protection lors des crashs, l'AGARD/AMP doit promouvoir les éléments suivants au sein de la communauté aérospatiale:

- le besoin d'inclure aux essais d'évaluation des systèmes aéronautiques une estimation des possibilités de lésions sur la base d'examens pratiqués à l'intérieur des mannequins en vue d'identifier les différentes blessures opérationnelles possibles, comme c'est fréquemment le cas dans l'industrie automobile;
- le besoin de développer une famille de mannequins de tailles différentes, afin de couvrir l'ensemble du personnel navigant, y compris les équipages féminins;
- le besoin de développer une instrumentation améliorée, y compris des enregistreurs d'accélération, des accéléromètres angulaires fiables, des systèmes embarqués d'acquisition et de traitement des données sur mannequins etc... afin d'améliorer les techniques d'évaluation des blessures et d'apporter une aide pour le traitement des données enregistrées mannequins;
- le besoin d'assurer un coût d'acquisition initial acceptable, utilisation et maintenance des mannequins comprises;
- l'exploitation de modèles informatiques validés en tant que substituts de l'homme, afin de réduire la demande d'essais à l'impact et d'éjection.

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Preface

Anthropomorphic dummies for crash and escape system testing have been used by military and civilian agencies for many years to assess, develop and standardize safer occupant protective systems for land and air vehicles. The automotive industry has spent considerable effort in designing crash test dummies that are biofidelic; i.e., dummies that duplicate the properties of a representative human subject on which injury risk is to be assessed. The major adult crash test dummies currently in use are the Hybrid II and its development into the Hybrid III for frontal impacts, and Side Impact Dummy (SID), Biofidelic Side Impact Dummy (BIOSID) and European Side Impact Dummy (EUROSID 1) for side impact tests. The US Air Force developed the Advanced Dynamic Anthropomorphic Manikin (ADAM) to test advanced ejection systems. More recently, biodynamic analytical models such as MAthematical DYnamical MOdel (MADYMO) and Articulated Total Body (ATB) model have been developed to simulate human responses and injuries associated with vehicular impacts.

The Aerospace Medical Panel (AMP) held a very successful symposium on Aircraft Accidents: Trends in Aerospace Medical Investigation Techniques (AGARD-CP-532) in Cesme, Turkey, 27 April - 1 May 1992. At that symposium, several papers described the use of dummies and mathematical simulations for studying crash phenomena. That Fall, at its 74th Business Meeting, the AMP accepted a proposal from its Biodynamics Committee for the formation of a Working Group to review the status and direction of the technology of aircraft ejection and car crash test dummies and identify the salient research and development advances in manikins that will enhance future aerospace capabilities for reducing aircrew injury risk. Dr Ints Kaleps, Armstrong Laboratory, Wright-Patterson AFB (WPAFB), OH was brought in as an AMP Consultant to help define the objectives of the Working Group. Furthermore, it was mandated by the AGARD National Delegates Board that lessons learned by the automotive industry in developing crash test dummies were to form an essential part of the activities of the Working Group.

Working Group 21 (WG21): Anthropomorphic Dummies for Crash and Escape System Testing met four times. Meetings of WG21 were held at Armstrong Laboratory, WPAFB, US, 5-6 May 1994; Mariners Hotel, Frensham, Farnham, Surrey, UK, 29-30 September 1994; Defence and Civil Institute of Environmental Medicine (DCIEM), North York (Toronto), CA, 4-5 May 1995; and Hotel "Alt Heidelberg", Heidelberg, GE, 5-6 October 1995. Teams were formed to address eight topics:

- Adult Dummies: Past and Present†
  Smrcka*, Kaleps, Mertz, Bendjellal and Obergefell
- Biomechanical Impact Response Requirements: Current Adult Dummies
  Mertz*, Guccione, Schueler and Bendjellal
- Anthropometry: Current Adult Dummies
  Kaleps* and Obergefell
- Injury Assessment
  Morgan*, Schueler, Poirier, Guccione, Mertz and Kaleps
- Instrumentation and Data Acquisition
  Blaker*, Malo and Kaleps
- New Developments and Special Features††
  Kaleps*, Mertz, Bendjellal, Morgan and Schueler
- Data Bases and Analytical Modeling
  Wismans* and Obergefell
- Dummy Users
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††Dr James A. Newman, President, Biokinetics and Associates, Inc. 2470 Don Reid Drive, Ottawa, Ontario, K1H 8P5, CA joined WG21 as a technical contributor, commencing with the meeting at DCIEM.

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List of Acronyms

A/D	analog to digital
ADAC	Allgemeiner Deutscher Automobil Club
ADAM	Advanced Dynamic Anthropomorphic Manikin
AFB	Air Force Base
AFGS	Air Force Guide Specifications
AGARD	Advisory Group for Aerospace Research and Development
AIS	Abbreviated Injury Scale
AL	Armstrong Laboratory
AMP	Aerospace Medical Panel
AMRL	Aerospace Medical Research Laboratory (now AL)
ams	"auto motor und sport" magazine
APR	Association Peugeot-Renault (now LAB)
APROD	Association Peugeot-Renault Omnidirectional Dummy
ARL	Alderson Research Laboratories
AS	SAE Aerospace Standard
ASCC	Air Standardization Coordinating Committee
ASIS	anterior-superior iliac spine
ATB	Articulated Total Body
ATCOM	Army Aviation Applied Technology Directorate
ATD	anthropomorphic test device
ATF	Airdrop Test Flight
BAST	Bundesanstalt für Strassenwesen Bergisch Gladbach
BB	Bean Bag
BIOSID	Biofidelic Side Impact Dummy
BSI	British Standards Institution
CAA	Civil Aviation Authority
CAMAC	Computer Automated Measurement and Control
CAMI	Civil Aeromedical Institute
CAMIX	Experimental child dummy from CAMI
CEV	Centre d'Essais en Vol
CEVA	Centre d'Essais Véhicules Automobiles
CFC	Channel Frequency Class
CFR	Code of Federal Regulations
CG	center of gravity
CHS	Centre for Human Sciences
CMVSS	Canadian Motor Vehicle Safety Standard
CPU	Central Processing Unit
CRABI	Child Restraint Air Bag Interaction
CREST	Crew Escape Systems Technologies
CVS	Crash Victim Simulator
DAS	data acquisition system
DCIEM	Defence and Civil Institute of Environmental Medicine
DRA	Defence Research Agency
DR	dynamic response
DRI	Dynamic Response Index
ECE	Economic Commission of Europe
EEC	European Economic Community
EEVC	European Experimental Vehicle Committee
EU	European Union
EUROSID	European Side Impact Dummy
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FE	finite element

FM	frequency modulation
FMVSS	Federal Motor Vehicle Safety Standard
FTSS	First Technology Safety Systems
GARD	Grumman-Alderson Research Dummy
GEBOD	GEnerator of BOdy Data
GM	General Motors Corporation
GSI	Gadd Severity Index
HIC	Head Injury Criterion
HSRI	Highway Safety Research Institute (now UMTRI)
HUD	Head-Up Display
IARV	Injury Assessment Reference Value
IBM	International Business Machines
IDDAS	Intelligent Dummy Data Acquisition System
IEEE	Institute of Electrical and Electronics Engineering
INRETS	Institut National de Recherche sur les Transports et leur Sécurité
IRIG	International Range Instrumentation Group
ISO	International Organization for Standardization
JAR	Joint Aviation Regulations
JPATS	Joint Primary Aircraft Training System
KEAS	Knots Equivalent Air Speed
KIAS	Knots Indicated Air Speed
KT	Kayser Threde
LAB	Laboratoire d'Accidentologie et de Biomécanique
LAMAS	Laboratoire de Médecine Aérospatiale
LRE	Limb Restraint Evaluator
MADYMO	MAthematical DYnamical MOdel
MHD	magnetohydrodynamic
MIDAS	Manikin Integrated Data Acquisition System
MIL STD	Military Standard
MIRA	Motor Industry Research Association
MPL	Medical Plastics Laboratory
MSC	Maximal Strain Criterion
MVMA	Motor Vehicle Manufacturers Association
NASA	National Aeronautics and Space Administration
NASS	National Accident Sampling System
NATO	North Atlantic Treaty Organization
NAWC	Naval Air Warfare Center
NBDL	Naval Biodynamics Laboratory
NBS	National Bureau of Standards
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
NIAR	National Institute for Aviation Research
NIST	National Institute of Standards and Technology
ONSER	Organisme National de la Sécurité Routière (now INRETS)
OPAT	Occupation Protection Assessment Test
OSU	Ohio State University
PC	personal computer
PCM	pulse code modulation
RAE	Royal Aerospace Establishment (now DRA (Farnborough))
RAF SAM	Royal Air Force School of Aviation Medicine
SAE	Society of Automotive Engineers
SID	Side Impact Dummy
SRL	Systems Research Laboratory

TAD	Trauma Assessment Device
3D	three dimensions
TLI	Triplex Laceration Index
TNO	Netherlands Organisation for Applied Scientific Research
TRC	Transport Research Center
TRL	Transport Research Laboratory
TRRL	Transport and Road Research Lab (now TRL)
TSO	Technical Standards Order
TTI	Thoracic Trauma Index
2D	two dimensions
UMTRI	University of Michigan Transportation Research Institute
USAARL	United States Army Aeromedical Research Laboratory
USAF	United States Air Force
UTAC	Union Technique de l'Automobile, du Motocycle et du Cycle
V*C	Viscous Criterion
VIP	Very Important People
WADC	Wright Air Development Center (now WPAFB)
WG3	Working Group 3 (Instrumentation) of ISO/Technical Committee (TC) 22/Sub-Committee (SC) 12
WG5	Working Group 5 (Anthropomorphic Test Devices) of ISO/Technical Committee (TC) 22/Sub-Committee (SC) 12
WPAFB	Wright-Patterson Air Force Base

Chapter 1

Introduction

1.1 BACKGROUND

Anthropomorphic dummies are mechanical surrogates of the human body. Dummies are also called anthropomorphic test devices (ATDs) and manikins. They are used as test devices by the automotive and aircraft industries and regulatory bodies, and the military to evaluate vehicle safety in crash and escape system environments. Dummies are designed to perform two basic functions. Earlier versions were used strictly for loading the vehicle dynamically, and required only weight and size in their design. The second type of dummy, used to assess type and severity of injury, is designed to mimic human dynamic impact response. These dummies require a sensor suite of instrumentation to measure impact loading of different body parts to assess injury risk [1.1 & 1.2].

1.2 SCOPE

The scope of this Advisory Report is restricted to adult dummies for crash and escape system testing. Only ATDs and mathematical simulations developed and used in the NATO countries are described. Other specialized dummies are designed for water immersion, thermal testing, fragment capture, ballistic impact, pedestrian impact, etc. These dummies, such as LIFEMAN used in ballistic testing, have not been considered, but are included in Chapter 9: Dummy Users, when organizations have identified them in their questionnaires. Also not considered is the significant work currently being conducted on child and infant crash test dummies by the TNO Crash-Safety Research Centre (Schoemakerstraat 97, PO Box 6033, 2600 JA Delft, The Netherlands), and the Society of Automotive Engineers (SAE) (400 Commonwealth Drive, Warrendale, PA 15096-0001, USA). Information on this important work can be obtained from a variety of sources [1.3 to 1.5]. There are also numerous anthropomorphic models of various body parts that are used for automotive subsystem testing of occupant protection. These are not discussed in this Advisory Report, but information regarding biofidelic attributes and deficiencies, injury-predictive measurement capabilities plus relevant references on these body parts can be found in Mertz [1.6]. Head forms and test standards to assess the protective quality of helmets are described in Chapter 7.

1.3 DUMMY DESIGN REQUIREMENTS

The principal design attributes of a dummy to serve as an effective human surrogate, including suggestions by Roberts [1.2] and Mertz [1.1 & 1.6], have been listed as anthropometry, biofidelity, repeatability, reproducibility, durability, measurement capability, sensitivity, simplicity and ease of use. In practice, compromises between several different requirements are made to produce the final dummy design.

1.3.1 Anthropometry

The dummy should have similar shape, mass distribution and joint articulation to that of the human.

1.3.2 Biofidelity

The dummy should duplicate the biomechanical response behaviour of a living human exposed to the same impact conditions. A high level of biofidelity is required to assess injury risk.

1.3.3 Measurement Capability

The dummy should be instrumented to provide measurements of appropriate forces, moments, deflections and accelerations.

1.3.4 Repeatability

The dummy should give the same response (output) to the same impact (input) conditions for repeated tests. Repeatability is assessed from peak responses to repeated tests with the same dummy. A Coefficient of Variation (= standard deviation/mean response) of 10% is generally considered an acceptable measure of repeatability, though figures down to 3% can be obtained.

1.3.5 Reproducibility

Different dummies of the same design should give identical responses to similar impacts. Specific details on design and performance specifications may be found in users manuals and/or Federal regulations.

1.3.6 Durability

Durability implies that the dummy should remain structurally sound following an impact and, moreover, its responses must remain biofidelic and repeatable. In some instances, durability is not a requirement. For example, dummies with frangible elements are sometimes used to investigate the breaking of body bones.

1.3.7 Sensitivity

The dummy should not be sensitive to extraneous conditions such as temperature and humidity effects that would affect its biofidelity and repeatability.

1.3.8 Simplicity and Ease of Use

The dummy should be easy to calibrate, require minimal external support equipment and be readily reparable. Dummy parts should be easy to change and replace.

1.4 REPORT OBJECTIVES AND FORMAT

This Advisory Report is a review of developments in, and the status of, escape and crash test dummies. It describes the work conducted by Working Group 21 in a logical sequence of chapters as follows:

- Compilation of past and current dummies
- Biomechanical impact response requirements of current adult dummies
- Anthropometric design data of current adult dummies
- Review of injury tolerance criteria currently in use
- Instrumentation and data acquisition capabilities for measuring dummy responses
- New developments and special features regarding dummy developments
- Mathematical models as human surrogates
- Compilation of organizations in NATO using dummies for defense-oriented aerospace applications

1.4.1 Adult Dummies: Past and Present

A historical review is given in Chapter 2 of the important manikins developed for assessing protective systems in both road vehicle and aircraft system testing. Dummy type, intended application and pertinent technical features are given for each dummy in tabular form. More detailed information, including illustrations, is given for the following:

- Hybrid II (Part 572) - mid-size adult male; frontal impact
- Hybrid III - mid-size and large males, small female; frontal impact
- SID, BIOSID and EUROSID 1 - mid-size males; side impact
- ADAM - small and large males; ejection phenomena

1.4.2 Biomechanical Impact Response Requirements: Current Adult Dummies

The focus in Chapter 3 is on the human biomechanical response requirements to mechanical stimuli. Because of human response variability and uncertainty as to validity, the biomechanical response requirements are usually given as upper and lower limits (or corridors). Dummy parts responding within these boundaries are considered to have sufficient biofidelity to be used in testing. Biomechanical impact response requirements are given for:

- Hybrid III family for head, neck, thorax and knee
- SID, BIOSID and EUROSID 1 for head, neck, thorax, shoulder, abdomen, and pelvis
- ADAM for joint motions, spinal response and durability

1.4.3 Anthropometry: Current Adult Dummies

Chapter 4 deals with general body dimensions and masses of the major dummies currently in use. Mass properties of individual dummy body segments are also provided. Anthropometric details are given for:

- GARD/CG – 5, 50, and 95%ile dummies
- Hybrid II
- Hybrid III family
- Aerospace family
- ADAM family
- SID, BIOSID and EUROSID 1

1.4.4 Injury Assessment

Injury tolerance criteria for impact exposures based on sensor measurements are discussed in Chapter 5. Critical to evaluating injury risk is the set of Injury Assessment Reference Values (IARVs) developed by General Motors Corporation (GM) for different body parts that are widely used by the automotive industry. These values were set at low risk of significant injury level [1.1]. IARVs are given for:

- Hybrid III family for head, head/neck interface, chest, femur, knee, tibia and facial lacerations
- SID, BIOSID and EUROSID 1 for head, chest, abdomen and pelvis

The injury risk associated with the thoracolumbar spine in ejection is determined by the Dynamic Response Index (DRI), a number that is proportional to the peak load in a lumped mass model of the human spine during acceleration. The Acceleration Exposure Limit Method extends the DRI methodology to predict injury risk to multi-axis linear acceleration and angular velocity exposures. Both are described in Chapter 5 as is the Maximal Strain Criterion (MSC), a predictor of head injury.

1.4.5 Instrumentation and Data Acquisition

Data acquisition standards, sensors and data acquisition systems currently in use are described in Chapter 6. The standards were developed by the Society of Automotive Engineers (SAE J211 March 1995) and the International Organization for Standardization (ISO 6487) for use in the automotive industry. They set

accuracy tolerances for data channel parameters, including the transducers, recording system and data processors. Sensors that measure dummy responses are basically of three types: accelerometers, load cells for measuring forces and moments, and displacement/position transducers. Complete sensor location, type of measurement, and number of channels are given for:

- Hybrid II family
- Hybrid III family
- ADAM
- SID, BIOSID and EUROSID 1

Details for collecting data from test dummies are described for data acquisition systems:

- Off-board the test device
- On-board the test device
- On-board the dummy

1.4.6 New Developments and Special Features

Chapter 7 describes a number of new ATD features and some new developments in injury protection criteria. The following six new ATDs are discussed:

- Joint Primary Aircraft Training System (JPATS) male and female manikins designed to accommodate the larger US flying population
- MIDAS manikin with improved spine and pelvis, and built-in data handling capability
- Trauma Assessment Device (TAD-50M), a manikin developed to overcome some of the deficiencies of Hybrid III in automotive testing
- SID-IIs dummy - small female; side impact
- Pregnant female crash dummy
- Motorcycle dummy

Other topics described are:

- Upgrades to Hybrid III
- Head forms and helmet test standards
- Facial developments for assessing facial lacerations and fractures
- Neck developments for improved human-like performance
- New developments in constructing extremities for improved limb motion and durability
- Improved occupant protection predictions

1.4.7 Data Bases and Analytical Modeling

Chapter 8 describes the advantages of using computer simulations of the human body for studying crash and escape system phenomena. Three types of models can be distinguished: lumped mass, multi-body and finite element (FE) models. The most widely used multi-body models for occupant simulations are described in great detail. These are:

- Articulated Total Body (ATB) model, a three-dimensional coupled, rigid-body dynamical, computer simulation program
- MAthematical DYnamical MOdel (MADYMO), a software package, combining multi-body elements for dynamic analysis and FE concepts for transient analysis of structures

Data bases for Hybrid II, Hybrid III family, SID, BIOSID, EUROSID 1 and ADAM are available as indicated in the text. Some typical applications of human body dynamics in a variety of aviation environments are illustrated.

1.4.8 Dummy Users

The final section, Chapter 9, is a compilation of forty-one organizations within NATO involved in the use and maintenance of dummies for defense-oriented crash and escape system testing and evaluation. The dummy inventory, data acquisition and analysis capabilities, standards employed, and calibration facilities are described for each organization according to information made available.

1.4.9 References

An extensive reference list (271 references) complements this Advisory Report for those requiring further information.

Chapter 2

Adult Dummies: Past and Present

2.1 INTRODUCTION

In the available literature, dummies are defined as mechanical surrogates of the human being, developed to assess the injury potential for specific loading conditions and the operation of safety systems, devices, or procedures. In general, such anthropomorphic test devices (ATDs) are designed to reproduce human physical characteristics - anthropometry, mass distribution, stiffness, energy dissipation - with the goal of simulating human responses - trajectory, deformation, and acceleration. Many types of human surrogates have been developed. They can be separated into two main groups: whole body models commonly called crash test dummies, and models of various body parts. The first group is used by the automotive industry to evaluate occupant restraint systems. The aircraft industry also uses whole body dummies to assess ejection seat designs. The models in the second group are used as subsystem test devices. Tests evaluate the safety potential of a particular car part (interior design, steering assembly, etc.) or assess the protective characteristics of helmets (crash and sport helmets).

Dummy or model responses are measured with transducers. Typical measured responses are acceleration, loads and deformation, which are used to estimate the potential of human injuries - types and severities - assuming that the humans and the dummies are exposed to similar loading conditions.

ATDs are classified according to the size and impact environment for which they were developed - frontal or side impact. Typical adult dummy sizes used are the 5th-percentile female (small female), the 50th-percentile male (mid-size male) and the 95th-percentile male (large male). For instance, the 50th-percentile adult male dummy, the most widely used dummy size in road vehicle testing, approximates the median height and weight of the adult male population of the United States.

The quality of an anthropomorphic dummy as an injury predictive tool depends on nine essential characteristics: anthropometry, biofidelity, measurement capability, repeatability, reproducibility, durability, sensitivity, simplicity and ease of use (see explanations in Chapter 1).

2.2 HISTORY OF ATD DEVELOPMENT

The first whole body dummy was built in 1949. Called Sierra Sam, it was developed by Sierra Engineering Co. for the US Air Force (USAF). It and many other whole body dummies developed since then are summarized in Table 2-1. Most of the early dummies, such as the Mark I and Grumman-Alderson Research Dummy (GARD), were developed for ejection seat testing. Later, the automotive industry drove dummy improvements, with the development of the Very Important People (VIP) and Sierra series of dummies. Developed in 1972, the Hybrid II was the first ATD used in automotive compliance testing. The Hybrid III and the different side impact dummies have subsequently been developed for automotive testing. More recently, dummies for aerospace testing, such as the Advanced Dynamic Anthropomorphic Manikin (ADAM), have been constructed.

It is outside the scope of this chapter to report in detail on all of the developed ATDs. To give an overview of the history of aerospace and automotive dummies, the main developments that occurred from 1949 until 1989 are summarized in Table 2-1, including for each dummy, a brief description and its use. Further information is available in reports identified in the Reference column in the table. Presented in the following text, are more detailed descriptions of the most commonly used surrogates: Hybrid II, Hybrid III, Side Impact Dummy (SID), European Side Impact Dummy (EUROSID 1), Biofidelic Side Impact Dummy (BIOSID) and ADAM.

2.2.1 The Hybrid II Dummy

In 1972, General Motors Corporation (GM) developed the Hybrid II (also known as the Part 572, Subpart B dummy) to assess the integrity of lap/shoulder belt systems. It mimics the size, shape, mass, and arm and leg ranges of motion of a 50th-percentile adult male. Figure 2-1 is a photograph of this device. It is instrumented to measure linear acceleration of the center of gravity (CG) of the head and a specific point in its thoracic spine. In addition, axial femur loads can be recorded. In vehicle crash tests, the dummy shows good durability and serviceability. The Hybrid II was specified in the Federal Motor Vehicle Safety Standard (FMVSS) 208 as the device to be used for compliance testing of vehicles equipped with passive restraints in 1973 [2.1]. The Code of Federal Regulations (CFR), Title 49, Chapter V, Part 572, Subpart B, specified the procedures for the calibration testing of the various body components/segments. The Hybrid II is still used in this

Table 2-1
Summary of Adult Automotive and Aerospace Anthropomorphic Test Devices (ATDs) Used in the NATO Countries Since 1949.

Year	Dummy	Developed By/For	Sizes	Key Features	Type of Use	Reference
1949	Sierra Sam	Sierra Engineering Co. for the United States Air Force (USAF)	95[1]	Human-like exterior shape and body weight, articulated limb joints, limited instrumentation measurements, and poor repeatability.	Ejection seat and crash tests.	
1952	Mark I	Alderson Research Lab (ARL) for USAF and European Air Forces	95	Detailed representation of human segments. Neck and spine with ball-and-socket joints. Stiff articulations. Few prototypes developed.	Ejection seat.	
1956	Models F, B, & P	ARL for aerospace and automotive research	8 sizes 3 to 98	General purpose ATD similar to Mark I. Good motion capabilities suitable for ejection seat tests. No chest compliance, modular and widely used.	Ejection seat, Apollo landing, F-111 escape capsule, and tractor safety tests.	
1960	GARD/CG (Grumman-Alderson Research Dummy)	ARL with Grumman Aircraft Engineering for USAF and US Navy	8 sizes 3 to 98	Correct center of gravity (CG) and mass distribution with integrated sensors and telemetry instrumentation, including measurement of rotational stability, acceleration, and man-seat interface stresses.	Ejection seat. Used in all Navy programs. Still in use.	
1966	VIP Series (Very Important People)	ARL for Ford, General Motors (GM), and National Bureau of Standards (NBS)	5, 50, 95	Designed to meet automotive testing requirements for pelvic structure and spinal deformation. Rib cage fitted with hydraulic cylinders. Measurements included femur loads, and head and thoracic accelerations. VIP modified to VIP-50 A, the first standard automotive ATD.	Automotive crash tests. Not in use.	
1967	Sierra Stan	Sierra Engineering for automotive testing	50	Seated posture to automotive requirements. Vinyl skin and polyurethane foam flesh. Chest deformation measurement. Telescopic rods connect shoulder to sternum. Ball-and-socket design for neck and lumbar spine.	Automotive crash tests. Not in use.	
1968	Sophisticated Sam	GM and Sierra Engineering	50	Experimental frangible dummy. Frangible clavicles, humeri, radii, ulnas, femurs, tibiae, fibulae, and patellae. Did not have human-like dynamic fracture response.	Crash tests. Not in use.	[2.28]

[1] Numbers are percentiles of a population usually based on height and weight. The population varies between dummies and is described in more detail in Chapter 4.

Table 2-1 (continued)

Year	Dummy	Developed By/For	Sizes	Key Features	Type of Use	Reference
1970	Sierra Susie	Sierra Engineering	5	Same interior design as that of Sierra Stan. Total mass equals 50 kg.	Crash tests. Not in use.	
1970	TNO-10	TNO Road-Vehicles Research Institute	50	Simple design with no lower arms and only one lower leg.	Loading device for testing vehicle safety belts. Test device for ECE Regulation 16.	[2.29]
1972	Dynamic Dan	Wyle Lab and the USAF Aerospace Medical Research Laboratory (AMRL)	50	Human-like spinal column stiffness in Z-direction. Fiberglass "bones", and ball-and-socket shoulder and hip joints.	Ejection seat, vibration, and parachute opening tests.	[2.25]
1972	Hybrid II (Part 572)	GM	50	Based on the VIP-50 A ATD. Good repeatability, durability. Human-like shape, body weight, and range of motion for some joints. Instrumented to measure head, chest and pelvic accelerations, and femur loads. The first ATD for automotive compliance testing.	Automotive crash and aerospace tests. Federal Motor Vehicle Safety Standard (FMVSS) 208 and Federal Aviation Administration (FAA) standards tests. Still in use.	[2.1]
1972	Supermorphic	ARL and Vector an Aydin Co. for the US Navy	3 to 98	Designed for escape system testing in the Yankee Escape System Navy EA6B program. Sophisticated instrumentation to record loads and pressures. Too fragile for ejection tests.	Not in use.	
1972	OPAT (Occupant Protection Assessment Test)	David Ogle Ltd. and Motor Industry Research Association (MIRA) in UK for Transport Research Lab (TRL)	50	Human-like rib cage, floating scapular design. Good repeatability. Instrumentation includes head and thoracic accelerations, and femur loads.	Lap and shoulder belt system tests. Still in use.	[2.24]
1973	Repeatable Pete	University of Michigan Transportation Research Institute (UMTRI) for the US Motor Vehicle Manufacturers Association (MVMA)	50	Human-like head, neck and chest. Flexible thoracic and lumbar spines. Constant torque joints at major limb articulations. Same measurements as Hybrid II.	Automotive crash tests. Not in use.	[2.26]
1975	Hybrid II Type	Humanoid Systems for the US automotive industry	5, 95	Scaled Hybrid II shapes and features with similar instrumentation capabilities.	Automotive crash and aerospace tests.	

Table 2-1 (continued)

Year	Dummy	Developed By/For	Sizes	Key Features	Type of Use	Reference
1976	Hybrid III (Part 572)	Developed by GM. Based on the GM ATD-502, which was developed by GM for National Highway Traffic Safety Administration (NHTSA) in 1973	50	Human-like shape. Curved lumbar spine and biofidelic neck. Good biofidelic head for forehead impact, chest in blunt frontal impact, and knee impact response. Instrumentation may include 44 measurements, with head, thoracic and pelvic accelerations, neck loads, chest deflection, and leg loads. Excellent repeatability, reproducibility and durability.	Automotive crash tests. Passive restraint system tests. Automotive standard in US and future automotive standard in Europe. Used worldwide.	[2.2, 2.5, 2.35]
1979	APROD (Association Peugeot-Renault Omnidirectional Dummy)	Laboratoire d'Accidentologie et Biomecanique (LAB) (formerly Association Peugeot-Renault (APR)) in France under contract with European Economic Community (EEC)	50	Forerunner to EUROSID. Human-like chest, neck and abdominal responses in side impact. Instrumentation comprised of head, chest and pelvic accelerations, rib-to-spine displacement, and abdominal penetration (switch contact).	Automotive side impact research tests. Not in use.	[2.27]
1979	ONSER (Organisme National de la Securite Routiere)	Institut National de Recherche sur les Transports er leur Securite (INRETS) (formerly ONSER) under contract with EEC	50	Human-shaped thorax and flexible shoulder design. Measurement of the lateral displacement of the simulated rib cage relative to the spine.	Automotive side impact research tests. Not in use.	[2.34]
1979	MIRA	MIRA under contract with EEC	50	Articulated shoulder structure and a human-shaped rib cage. A unique pelvic structure instrumented to measure loads applied to the ilium, acetabulum and pubic symphysis. Measurement of individual rib loading.	Automotive side impact research tests. Not in use.	[2.34]
1979	SID (Side Impact Dummy) (Part 572)	University of Michigan Transportation Research Institute (UMTRI) for NHTSA	50	Modified Hybrid II with a specific chest design for side impact. Twelve accelerometer array in the chest.	Automotive side impact tests. FMVSS 214 standard test. In use worldwide.	[2.7 and 2.8]

Table 2-1 (continued)

Year	Dummy	Developed By/For	Sizes	Key Features	Type of Use	Reference
	Aerospace Test Dummy	Humanoid Systems for the US Navy	5, 50, 95 male & 5% female	Based on Hybrid II and Hybrid III with sit-stand construction. Increased strength for ejection environment.	Ejection tests	
1982	Tuff Kelly	Medical Plastics Laboratory (MPL)	5 sizes 45 kg to 102 kg	Rescue manikin with cast vinyl body supported by steel frame. Wire cable and springs allow joint movement.	Parachute testing, and escape and fireman training.	
1983	LRE (Limb Restraint Evaluator)	Systems Research Laboratories (SRL) and ARL for USAF	Large male	Human-like limb and joint motion, and high durability.	Wind blast effects and limb restraint device for effectiveness testing.	[2.23]
1986	ADAM (Advanced Dynamic Anthropomorphic Manikin)	SRL for USAF	Small & large males	Good approximation of human mass distribution and joint center locations. Human-like joint articulations and spinal response in Z-direction. Specific limb design. On-board data acquisition system.	Ejection seat, helicopter seat, and parachute tests. USAF Crew Escape Systems Technology (CREST) program.	[2.16 and 2.17]
1987	Hybrid III small female and large male	Society of Automotive Engineers (SAE)	5, 95	Pertinent responses scaled from Hybrid III 50th-percentile and comparable instrumentation.	Crash tests.	[2.6]
1989	EUROSID 1 (European Side Impact Dummy)	APR, INRETS, TNO, and TRL	50	A modification of EUROSID (1986) having unique neck, chest, abdomen and pelvis. Three ribs attached to spine by piston-cylinder assembly and spring-damper system. Measurements of rib-to-spine displacement, and abdominal and pelvic loads.	Automotive side impact tests. Test dummy for the Draft European Side Impact Regulation Economic Commision of Europe (ECE) 95. In use worldwide.	[2.18 and 2.19]
1989	BIOSID (Biofidelic Side Impact Dummy)	SAE	50	Modified EUROSID chest, abdomen, shoulder, and pelvis. Hybrid III head, neck and legs. Measurements of shoulder, chest and abdominal rib deflections. Loads at neck, shoulder, spinal, abdominal, and pelvic segments.	Used for evaluating advanced automotive side impact restraint systems.	[2.21]

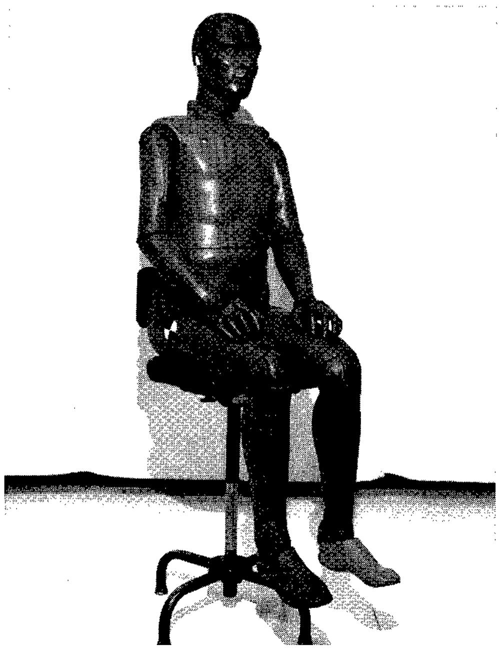

Figure 2-1
Hybrid II 50th-Percentile Male Dummy
(Courtesy of Defence and Civil Institute of Environmental Medicine, North York, ON, CA)

US regulation. Given some of its deficiencies in terms of biofidelity and measurement capabilities, its use in automotive testing has become limited, especially in Europe.

2.2.2 The Hybrid III Dummy

The Hybrid III was developed by GM in 1976 [2.2] as a Part 572, Subpart E dummy. It is also a 50th-percentile adult male dummy. Its specific features include a head with human-like impact response in the forehead area, an articulated neck, a curved lumbar spine, and constant-torque knee and shoulder joints (Figure 2-2). The head consists of an aluminum shell covered by vinyl skin having constant thickness over the cranium. The neck is a one-piece structure consisting of four asymmetric rubber segments bonded to aluminum disks and to end plates. A braided wire cable attached to end plates passes through the neck center. The top end plate is linked to the head with a single pivot joint. The chest of the dummy is comprised of six steel ribs linked on one end to a leather part representing the sternum and on the other end to a rigid spine. Each rib is covered with damping material. Because of this design, the compliance of the Hybrid III chest in pendulum impacts, i.e., the distributed loading, is comparable to that of the human. The shoulder has a rigid structure and the abdominal part is made of plastic foam. The lumbar spine is represented by a cylindrical curved rubber piece with two braided steel cables running through the center and attached to end plates. The pelvis consists of an aluminum casting of a human pelvic shape covered with a vinyl skin. Femurs and legs are made of steel shafts covered with a vinyl skin. Rubber pads are inserted in both knee areas under the skin. Ball joints are at the hip and ankle.

Compared with the Hybrid II, the Hybrid III head, neck, chest and knees have better impact response biofidelity. Biofidelity deficiencies [2.3] are the stiff shoulder design and stiff chest response under concentrated loading.

2.2.2.1 Instrumentation

The Hybrid III instrumentation is described in detail in Reference [2.4] and Chapter 6. It includes linear accelerometers in the head, chest and pelvis, and load cells in the cervical area and leg regions. An extensive number of data channels can be recorded with the fully instrumented dummy.

2.2.2.2 Hybrid III Applications

Given its design features and instrumentation potential, this dummy is used as an assessment device for occupant crash protection by car manufacturers, automotive suppliers, research laboratories, and various test centers worldwide. The Hybrid III will soon become a mandatory tool in the United States and Europe. More details on the Hybrid III characteristics, biofidelity, and responses in various impact conditions can be found in Reference [2.5]. Calibration procedures are specified in CFR, Title 49, Chapter V, Part 572, Subpart E. A user's manual, Engineering Aid 23, 1986, is available from the SAE [2.30].

2.2.2.3 Small Female and Large Male Hybrid III - Type Dummies

While the Hybrid III dummy gives excellent assessments of the effectiveness of automotive restraint systems for the mid-size adult male occupant, it provides no information concerning restraint systems effectiveness for large or small adult occupants. To fill this void, the Center for Disease Control awarded a grant in 1987 to Ohio State University (OSU) to develop a multi-sized Hybrid III-based dummy family. To support the OSU effort, the Mechanical Human Simulation Subcommittee of the Human Biomechanics and Simulation Standards Committee of the Society of Automotive Engineers

Figure 2-2
Hybrid III Family - (left to right: small female, 50th-percentile male, large male)
(Courtesy of General Motors Corporation, Warren, MI, USA)

(SAE) formed a Task Force of biomechanics, test dummy, transducer, and restraint-system experts. They defined the specifications for an adult small female dummy and a large male dummy having the same level of biofidelity and measurement capacity as the Hybrid III dummy [2.6]. Key body segment lengths and weights were selected for each dummy based on the anthropometry data for the extremes of the United States adult population. Geometric and mass scale factors were developed to assure that each body segment had the same mass density as the corresponding Hybrid III body segment. Other pertinent dimensions were scaled from their corresponding Hybrid III dimensions using the geometric scale factors.

The Hybrid III biomechanical response requirements for the head, neck, chest, and knee were scaled using the appropriate scale factors giving corresponding biofidelity response requirements for each size of dummy [2.1]. The Hybrid III design drawings were scaled using these geometric scale factors to produce design drawings for each dummy. This procedure gave assurance that each dummy, made according to its scaled drawings, would meet its scaled biofidelic requirements. The two dummies were instrumented identically to the Hybrid III dummy. Calibration procedures are specified in SAE Engineering Aid 25, 1995, for the small female [2.31] and Engineering Aid 26, 1995, for the large male [2.32]. Both dummies are commercially available - see Figure 2-2.

2.2.3 The SID

The Side Impact Dummy (SID) was developed in 1979 by University of Michigan Transportation Research Institute (UMTRI) under contract with National Highway Traffic Safety Administration (NHTSA) [2.7 and 2.8]. The SID is a Part 572, Subpart D (or Hybrid II) dummy modified for side impact testing. It features a unique chest structure including a hydraulic shock absorber that links five interconnected steel ribs to the spine, providing human-like responses. The SID has no arm or shoulder structure. The chest is covered with plastic flesh. The other body segments are those of the Hybrid II. Exterior size and shape are close to those of a 50th-percentile adult male. Major biofidelic deficiencies are the lack of a shoulder load path, no elasticity in the thoracic compliance, and a very heavy rib mass. Figure 2-3 illustrates the SID dummy.

2.2.3.1 Instrumentation

Instrumentation includes measurement of linear accelerations of the head, thorax and pelvis. In

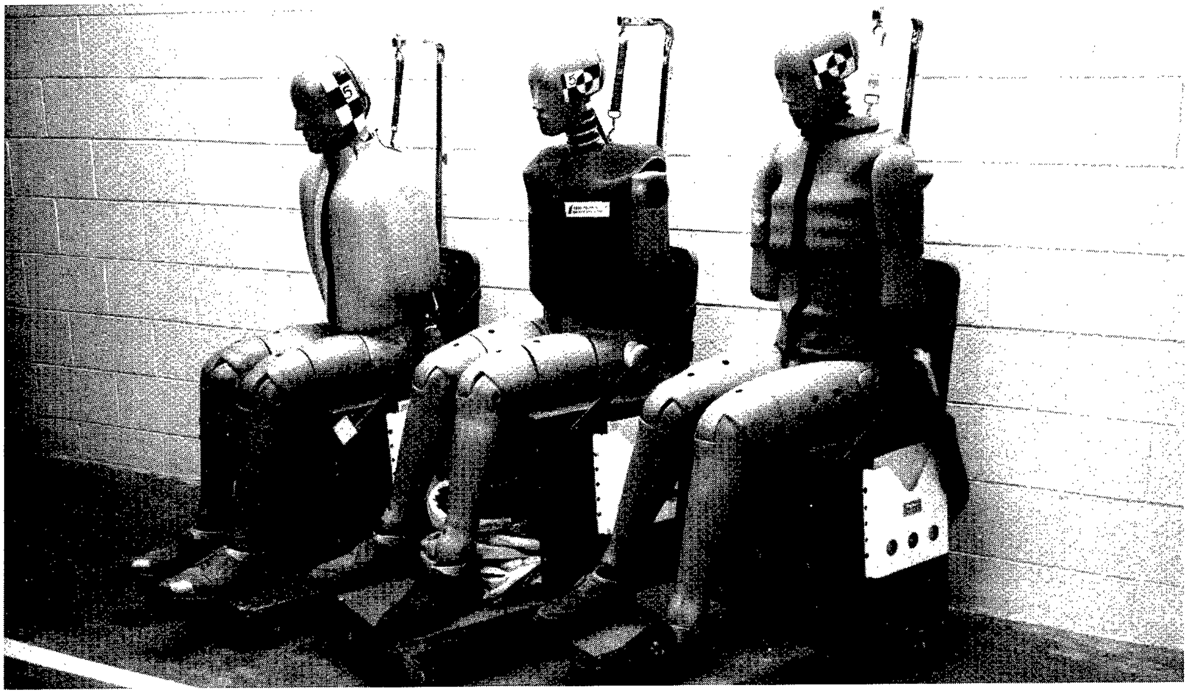

Figure 2-3
Side Impact Dummies - (left to right: SID, BIOSID and EUROSID 1)
(Courtesy of General Motors Corporation, Warren, MI, USA)

particular, the thorax incorporates an array of twelve accelerometers to measure the behavior of the spine and the ribs. The injury potential to the thorax is calculated using the Thoracic Trauma Index (TTI), which is a function based on the rib acceleration and that of the lower spine [2.9] - see Chapter 5.

2.2.3.2 SID Applications

The SID is the tool defined by NHTSA for the assessment of vehicle side impact protection according to the test procedure of FMVSS 214 [2.10]. The SID dummy was evaluated in various test conditions where its responses to impact were compared with those of BIOSID and EUROSID 1. The corresponding results can be found in publications [2.11] through [2.15].

2.2.4 The EUROSID 1

The European Side Impact Dummy (EUROSID 1) is designed for the evaluation of occupant safety in lateral impact. It was developed and constructed by several European laboratories working together as an ad-hoc group under the auspices of the European Experimental Vehicle Committee (EEVC). Extensive development of EUROSID was performed by Association Peugeot-Renault (APR) and Institut National de Recherche sur les Transports et leur Securite (INRETS) in France, TNO in the Netherlands, and Transport Research Laboratory (TRL) in the United Kingdom. Four prototypes were built and evaluated in 1986. This version, known as EUROSID Production Prototype, was evaluated worldwide between 1987 and 1989 by governments, the car industry, International Organization for Standardization (ISO), and SAE. Based on this international evaluation, the dummy's biofidelity, durability, and instrumentation were improved [2.18]. The dummy represents a 50th-percentile adult male and its final specification was established by EEVC in April 1989. The dummy is produced by Ogle Design in England and TNO.

The EUROSID 1 [2.19], as shown in Figure 2-3, consists of a metal and plastic skeleton, covered by foam and rubber flesh-simulants. The sitting height is 90.4 cm and its mass is 72.0 kg. The head is that of the

Hybrid III; i.e., an aluminum shell covered by a pliable vinyl skin. The neck is a composition of metal discs and rubber elements with special joints to the head and the chest, allowing a human-like head-to-chest motion. The thorax consists of three separate, identical ribs covered with flesh-simulating foam, attached to a rigid steel spine box by a piston-cylinder assembly and a spring-damper system. The shoulder has a special design to allow a direct impact exposure of the chest when the arm is rotated. The abdomen is a metal casting covered with a mass-carrying flesh-simulating foam. A solid rubber cylinder with a steel cable inside simulates the lumbar spine. The pelvis consists of two plastic iliac wings linked by a metal sacrum and covered with a foam and polyvinyl chloride skin. The arms are represented by upper arms (plastic skeleton and flesh) only, and the legs are those of the Hybrid III.

2.2.4.1 Instrumentation

The EUROSID 1 instrumentation includes linear accelerometers in the head, spine, ribs and pelvis. Rib-to-spine displacement can be measured for each rib. Loads to the abdomen and pelvis are measured by means of transducers.

2.2.4.2 EUROSID Applications

This dummy is included as a test device in the Draft European Side Impact Regulation ECE 48 [2.20].

2.2.5 The BIOSID

The Biofidelic Side Impact Dummy (BIOSID) was developed by SAE for side impact testing in 1989 [2.21], following international evaluations of SID and EUROSID [2.12 to 2.14]. The dummy was designed to have impact response biofidelity for the head, neck, shoulder, thorax, abdomen, and pelvis. The BIOSID uses the Hybrid III head, neck, and legs. The chest design is based on the "far side" mounted rib concept of Lau et al. [2.22], which allows 75 mm of rib deflection without permanent rib deformation. The shoulder and abdominal constructions are also made using this concept. Only the upper arm is simulated on BIOSID, as shown in Figure 2-3. The pelvis is a modification of the EUROSID pelvis with a crushable block in the H-point area (pivot center of torso and thigh). BIOSID instrumentation includes the following measurements:

- Linear acceleration of the head, shoulder, spine, thoracic and abdominal ribs, and pelvis
- Neck forces and moments
- Shoulder force and deflection
- Rib deflection in the chest and abdominal areas
- Forces of iliac wing, sacrum and pubic symphysis
- Same lower extremity instrumentation as that of the Hybrid III

A user's manual, SAE Engineering Aid 24 [2.33] is available with detailed assemble/disassemble instructions and calibration procedures.

2.2.6 The ADAM

In 1986, the Advanced Dynamic Anthropomorphic Manikin (ADAM) was developed by Systems Research Laboratories (SRL) under contract to the Armstrong Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base (WPAFB), Ohio [2.16 & 2.17]. ADAM is a fully instrumented, high fidelity manikin used as a sophisticated test device to support acceleration and ejection system tests. ADAM was developed for the USAF advanced development ejection seat program, Crew Escape Systems Technologies (CREST). ADAM has direct applications in other important areas of replicating a human body's dynamic response during potentially dangerous conditions; i.e., for experimental parachute tests, helicopter seat crashworthiness tests, etc.

The ADAM's biofidelic attributes are summarized as follows:

- ADAM body segments approximate human surface contours, weights, moments of inertia, CGs and joint center locations
- Ranges of motion of 39 revolute joints replicate human articulations
- "Soft stops" which yield human-like, non-linear torque deflection variances for each articulation, as well as providing absorption of impact loads
- Independently adjustable friction mechanisms designed into each joint (excluding wrist and sternoclavicular joints) to provide for passive muscle resistive forces
- Biodynamic spinal response from an integrated spring-damper element that provides for both low amplitude vibration and high impact exposures.

The limbs are constructed from stainless steel and the torso from an aluminum alloy. A heat-cured vinyl plastisol provides the proper outside flesh-covered body contours, and represents the characteristics of human flesh. Vinyl plastisol foam between outer and inner layers of vinyl plastisol is compliant and represents soft tissue. All of the vinyl plastisol components for the small ADAM were developed and supplied by Alderson

Research Laboratories (ARL), Stamford, CT, and for the large ADAM by Humanetics Inc., Carson City, CA.
The ADAM spinal system was designed to replicate the human spine's elasticity in the vertical direction. The Z-axis human spinal-response qualities are incorporated into ADAM by using a mechanical spring-damper system in the spine. This concept allows for human-like dynamic deformation in the Z-direction. Figure 2-4 illustrates ADAM's design. By providing a realistic spinal system, the seated, whole-body CG of ADAM varies with the force applied and results in a realistic response to loading due to seat motion.

ADAM was produced in two different sizes, small and large representing the USAF male flying population, weighing, respectively, 64.2 kg and 98.3 kg. Both manikins are available.

2.2.6.1 Instrumentation

Instrumentation for ADAM includes linear and angular accelerometers, neck and lumbar load cells, and joint angular position sensors. The data from these sensors are collected in a processing system located in ADAM's chest. This on-board data acquisition system can collect 64 channels of data at 10,000 samples/s for 12s for downloading following test completion.

2.3 CONCLUSION

Dummy development has been a continuous process since the 1940s with each new dummy design building on the lessons learned from earlier designs and new biomechanical response data. Already, the NHTSA is working on the Trauma Assessment Device (TAD-50M), the US military is preparing to build a large male manikin and a small female manikin (JPATS dummies), and the US car industry is developing a small female designated the SID IIs dummy - see Chapter 7.

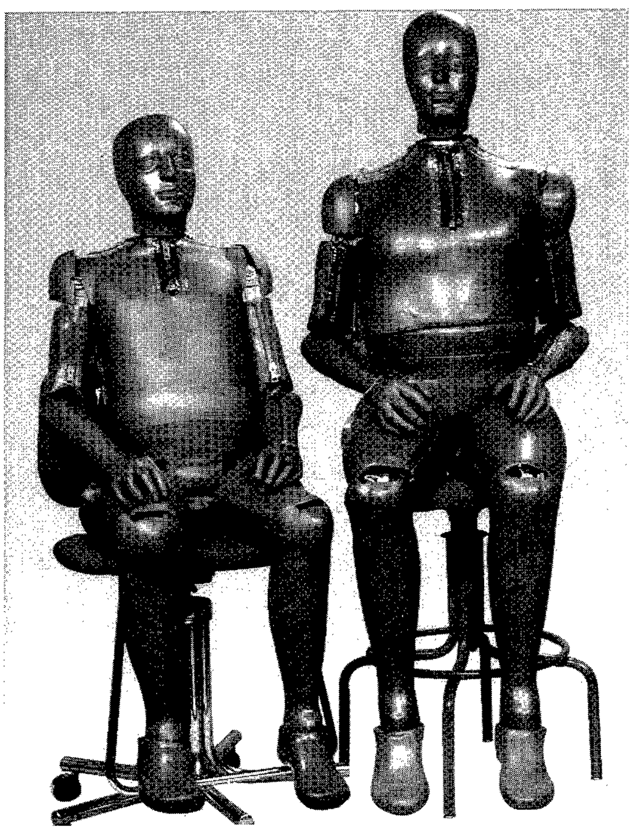

Figure 2-4
Advanced Dynamic Anthropomorphic Manikin - ADAM
(left to right; small and large ADAM males)
(Courtesy of Armstrong Laboratory, Wright-Patterson Air Force Base, OH, USA)

Chapter 3

Biomechanical Impact Response Requirements: Current Adult Dummies

3.1 HYBRID III SMALL FEMALE, MID-SIZE MALE AND LARGE MALE DUMMIES

The mid-size, adult male, Hybrid III type dummy was developed by General Motors Corporation (GM) in the early 1970's to improve the impact biofidelity of the 50th-percentile dummy used in crash testing to evaluate automotive restraint systems [3.1 & 3.2]. The size, weight and range of motion of various limb joints were based on the values given in SAE J963 [3.3]. Requirements for the overall body dimensions were taken from the anthropometric studies of Hertzberg et al. [3.4], and the US Department of Health, Education and Welfare [3.5]. The requirements for range of motion were based on the work of Glanville and Kreezer [3.6]. Dimensions for the head were based on the analysis of Hubbard and McLeod [3.7]. For the adult size, Hybrid III types of small female and large male dummies, requirements for body length dimensions and weights were based on the analysis done by Schneider et al. [3.8]. The development of these two dummies is summarized by Mertz et al. [3.9]. For the mid-size Hybrid III dummy, biomechanically-based impact response requirements were defined for forehead impacts, fore-and-aft neck bending, blunt sternal impacts, knee impacts and drawer motion of the tibia relative to the femur. These requirements were scaled by Mertz et al. [3.9] to give biomechanically-based response requirements for the small female and large male dummies. The following is a summary of these requirements.

3.1.1 Forehead Impact Requirements

The biomechanical forehead impact response requirements for the mid-size Hybrid III dummy are limits on the peak resultant acceleration of the head center of gravity (CG) for a 376 mm drop of the head onto a flat, rigid impact surface. The acceleration limits are based on an analysis of cadaver tests [3.10 & 3.11]. The acceleration limits for the Hybrid III type, small female and large male dummies were scaled from the mid-size limits using the scaling technique described by Mertz et al. [3.9]. The biomechanically-based limits are given in Table 3-1 for the three dummy sizes. These limits are verification requirements for peak resultant head accelerations for flat, rigid-surface forehead impacts of the respective dummies.

For forehead impacts to padded surfaces, Mertz [3.10] has shown that head mass and shape are the factors which control the head acceleration response. Since the head masses and geometries of the dummies meet their corresponding mass and size guidelines, their responses to padded forehead impacts are human-like.

3.1.2 Neck Bending Response Requirements

The biomechanical fore-and-aft neck bending requirements for the Hybrid III type mid-size male dummy are based on the human volunteer and cadaver testing done by Mertz and Patrick [3.12]. These requirements were scaled by Mertz et al. [3.9] to give fore-and-aft neck bending requirements for the small female and large male dummies. The neck flexion corridor is given in Figure 3-1 and the one for extension is given in Figure 3-2. The coordinates of the corridors for the three dummies are given in Table 3-2.

Table 3-1
Peak Resultant Head Acceleration Requirements
for Forehead Impacts of the Hybrid III Types
of Mid-Size Male, Small Female and Large Male Dummies
Produced by Dropping the Head from 376 mm onto a Flat, Rigid Surface

Hybrid III Adult Dummies	Peak Resultant Head Acceleration (G)		
	Lower Limit	**Mid Point**	**Upper Limit**
Mid-Size Male	225	250	275
Small Female	240	270	295
Large Male	220	245	265

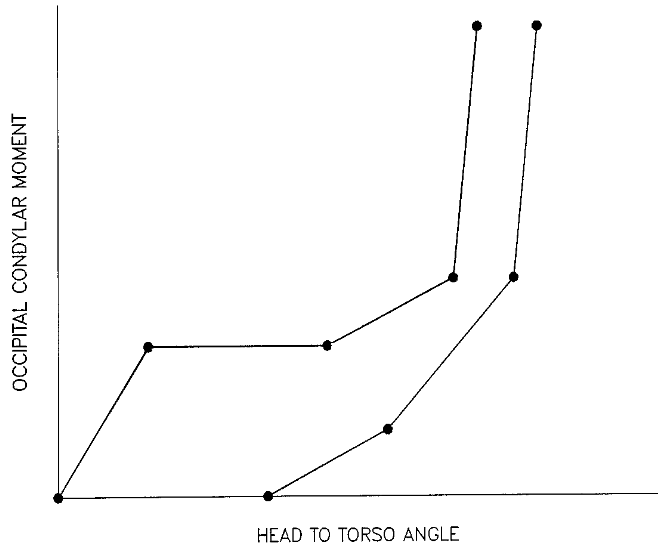

Figure 3-1
Neck Flexion Corridor
See Table 3-2 for Coordinates

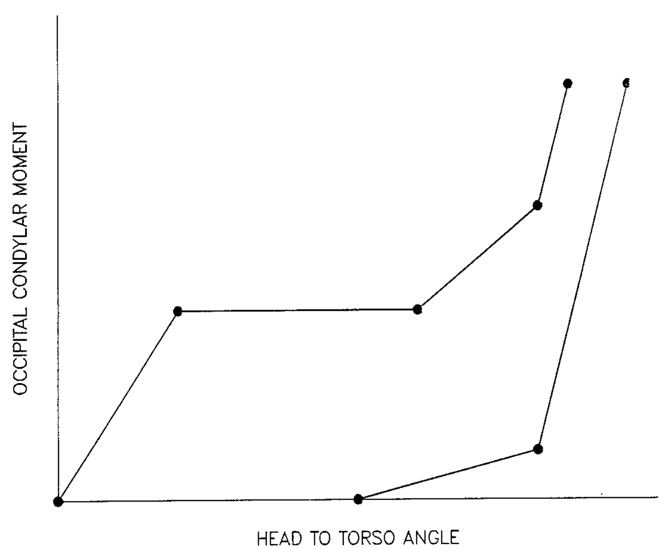

Figure 3-2
Neck Extension Corridor
See Table 3-2 for Coordinates

Table 3-2
Neck Flexion and Extension Response Corridor Coordinates
for Hybrid III Types of Mid-Size Male, Small Female and Large Male Dummies

Corridor Description	Mid-Size Male Angle (°)	Mid-Size Male Moment (Nm)	Small Female Angle (°)	Small Female Moment (Nm)	Large Male Angle (°)	Large Male Moment (Nm)
Flexion Corridor						
	0	0	0	0	0	0
Upper	15	61	16	33	14	83
Boundary	45	61	49	33	43	83
Coordinates	66	88	72	48	64	120
	70	190	77	104	68	258
Lower	35	0	38	0	34	0
Boundary	55	27	60	15	53	37
Coordinates	76	88	83	48	73	120
	80	190	88	104	77	258
Extension Corridor						
	0	0	0	0	0	0
Upper	20	31	22	17	19	42
Boundary	60	31	66	17	58	42
Coordinates	80	48	88	26	77	65
	85	68	93	37	82	92
Lower	50	0	55	0	48	0
Boundary	80	8	88	4	77	11
Coordinates	95	68	104	37	92	92

To assess the fore-and-aft bending biofidelity of the neck, the head and neck structure is first mounted to the free-end of a rigid pendulum [3.13 to 3.15]. Then the pendulum is released from a height to produce the desired articulation of the neck for flexion or extension. The resulting moment about the occipital condylar axis versus the head-to-pendulum angle must lie within the prescribed corridor shown in Figure 3-1 or Figure 3-2 for sagittal plane flexion or extension, respectively.

3.1.3 Sternal Force - Deflection Requirement

The biomechanical sternal impact response requirement for the mid-size Hybrid III type dummy is based on the cadaver impact tests of Kroell et al. [3.16] and is shown in Figure 3-3. This requirement was scaled by Mertz et al. [3.9] to give biomechanical requirements for the small female and large male dummies. The coordinates of the corridor for the three dummies are given in Table 3-3. Note that the impactor used for the small female dummy is lighter (14.0 kg) than that used for the mid-size and large male dummies (23.4 kg). This was done so that the small female chest would not be damaged during the test for biofidelity. Again, the assessment for biofidelity is determined through the response verification test for each dummy [3.13 to 3.15].

3.1.4 Knee Impact Requirement

The biomechanical knee impact response requirement for the mid-size male, Hybrid III type dummy is based on the cadaver tests of Horsch and Patrick [3.17]. Limits are placed on the peak impact force when the knee is impacted with a 5-kg rigid pendulum impactor at 2.1 m/s. These limits were scaled by Mertz et al. [3.9] to give biomechanical requirements for the small female and large male dummies. The impact response requirements for the three dummies are given in Table 3-4. Note that the small female is to be struck with a lighter mass (3.0 kg) to prevent damage to the knee during the test. Again, the assessment for biofidelity is determined through the response verification test for each dummy [3.13 to 3.15].

3.1.5 Knee Drawer Requirement

The Hybrid III type dummies are designed to mimic the shearing motion ("drawer" response) that can occur between the tibia and the femur when the leg is bent 90 degrees at the knee. The stiffness limits for the mid-size male are based on cadaver tests [3.18]. These limits were scaled by Mertz et al. [3.9] to give stiffness limits for the small female and large male dummies. Drawer stiffness requirements for the three dummies are given in Table 3-5. Again, the assessment for biofidelity is determined through the response

verification test for each dummy [3.13 to 3.15]. For the mid-size male and large male dummies, the test is conducted with a 12-kg pendulum at an impact speed of 2.75 m/s. To avoid damaging the small female, the test is conducted with a 7.26-kg pendulum, but with the same impact velocity.

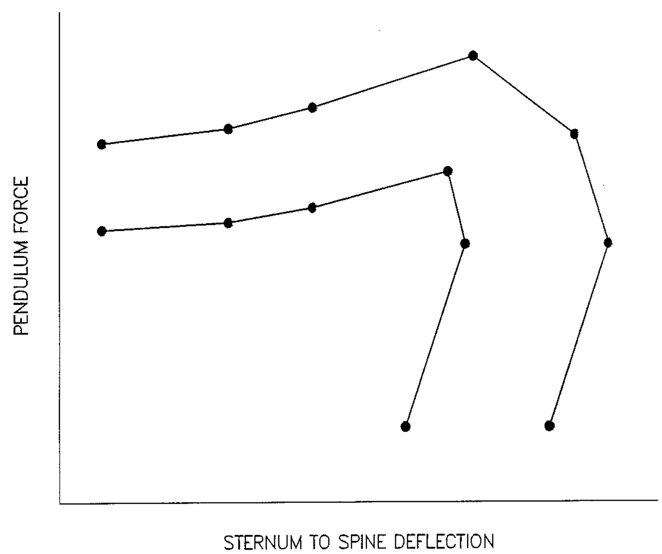

Figure 3-3
Thoracic Response Corridor
See Table 3-3 for Coordinates.

Table 3-3
Chest Response Corridor Coordinates for Hybrid III Types
of Mid-Size Male, Small Female and Large Male Dummies
Subjected to 6.7 m/s Pendulum Impacts

Corridor Description	**Mid-Size Male Struck by a 23.4 kg Pendulum**		**Small Female Struck by a 14.0 kg Pendulum**		**Large Male Struck by a 23.4 kg Pendulum**	
	Defl. (cm)	**Force (kN)**	**Defl. (cm)**	**Force (kN)**	**Defl. (cm)**	**Force (kN)**
Upper Boundary Coordinates	0.64	4.36	0.51	3.06	0.66	4.85
	2.54	4.54	2.08	3.18	2.64	5.07
	3.81	4.80	3.12	3.36	3.96	5.34
	6.22	5.43	5.08	3.79	6.48	6.05
	7.75	4.45	6.32	3.11	8.08	4.94
	8.26	3.11	6.76	2.17	8.59	3.47
	7.37	0.89	6.02	0.63	7.67	0.98
Lower Boundary Coordinates	0.64	3.29	0.51	2.30	0.66	3.65
	2.54	3.38	2.08	2.38	2.64	3.78
	3.81	3.56	3.12	2.50	3.96	3.96
	5.84	4.00	4.78	2.80	6.07	4.45
	6.10	3.11	4.98	2.17	6.35	3.47
	5.21	0.89	4.24	0.63	5.41	0.98

Table 3-4
Peak Knee Impact Response Requirements
for the Hybrid III Types of Mid-Size Male,
Small Female and Large Male Dummies
Subjected to Pendulum Impacts at 2.1 m/s

	Mid-Size Male Struck by a 5.0 kg Pendulum	Small Female Struck by a 3.0 kg Pendulum	Large Male Struck by a 5.0 kg Pendulum
Lower Limit (kN)	4.72	3.45	4.91
Mid Point (kN)	5.25	3.83	5.46
Upper Limit (kN)	5.78	4.22	6.01

Table 3-5
Biomechanical Knee Drawer Stiffness Requirements
for the Hybrid III Types
of Mid-Size Male, Small Female and Large Male Dummies

	Mid-Size Male (kN/cm)	Small Female (kN/cm)	Large Male (kN/cm)
Lower Limit	1.26	1.09	1.37
Mid Point	1.49	1.29	1.62
Upper Limit	1.72	1.49	1.87

3.2 50TH-PERCENTILE, MALE SIDE IMPACT DUMMIES

The experts of the International Organization for Standardization (ISO) have established requirements [3.19 to 3.24] and a rating scheme [3.25 to 3.27] for assessing the biofidelity of the lateral impact responses of the head, neck, thorax, shoulder, abdomen and pelvis of side impact surrogates (dummies and mathematical models) of the 50th-percentile adult male. They also conducted an evaluation of the three side impact dummies, SID [3.28], EUROSID 1 [3.29] and BIOSID [3.30] relative to these biofidelic requirements [3.31 to 3.34]. While none of the dummies met all of the requirements, they concluded that both EUROSID 1 and BIOSID had sufficient biofidelity to be used in side impact testing. SID did not have sufficient biofidelity to be recommended for use [3.35].

The Working Group ISO/TC22/SC12/WG5 - Anthropomorphic Test Devices, is currently conducting a review of the biofidelic requirements of side impact surrogates. A number of concerns are being addressed. First, many of the cadaver specimens, whose responses were used to establish requirements, were extensively damaged by the impacts, making the data unsuitable for defining response requirements. Second, a number of test conditions were not well enough defined to be replicated. The WG5 experts are considering not using such cadaver data and test conditions in defining biofidelic requirements. In addition, the procedure used to normalize the data is being reviewed and data from recent biomechanical studies are being considered for inclusion in the analysis. Updates of the ISO information reports (ISO 9790-1 through 6) should be completed by 1998. The following is a summary of the current biomechanical impact response requirements developed by the ISO to assess the biofidelity of the 50th-percentile, adult male, side impact surrogates.

3.2.1 Lateral Head Impact Requirements

The ISO has defined two lateral head impact requirements [3.19], one based on the rigid surface cadaver impacts conducted by Hodgson and Thomas [3.36] and the other based on the padded surface cadaver impacts of Association Peugeot-Renault (APR) [3.37].

3.2.1.1 Rigid Surface Impact

The head is oriented with its sagittal plane at 35 degrees to the horizontal and is dropped from a height of 200 mm onto a flat, rigid horizontal surface. To be considered biofidelic, the peak resultant acceleration of the CG of the head must be between 100 to 150 G for this lateral head impact condition.

3.2.1.2 Padded Surface Impact

The head is oriented with its sagittal plane at 10 degrees to the horizontal and is dropped from a height of 1200 mm onto a flat, rigid surface which is covered with a 5-mm-thick rubber pad. The biofidelic requirement is for the peak resultant head acceleration to lie between 217 and 265 G.

3.2.2 Lateral Neck Flexion Requirements

The ISO has defined lateral neck flexion requirements [3.20] based on three studies; the human volunteer data of Ewing et al. [3.38 & 3.39], the human volunteer data of Patrick and Chou [3.40] and the cadaver tests conducted at APR [3.41].

3.2.2.1 Requirements Based on Ewing Data

A rigid chair with a horizontal seat pan and a vertical seat back is securely fastened to an accelerator (Hyge) sled in a sideward facing direction. A vertical side board is attached to the seat to restrict sideward motion of the dummy's torso and legs relative to the seat. The dummy is restrained by an aviation lap-and-shoulder harness system. When the sled is subjected to a 7-G sled pulse, the dummy's responses must meet the following requirements:

- Horizontal displacement of first thoracic vertebra (T1) with respect to sled: 46 to 63 mm
- Horizontal acceleration of T1: 12 to 18 G
- Angular rotation of head with respect to X-Z plane: 44 to 59 degrees
- Angular twist of head: 32 to 45 degrees
- Head acceleration: lateral, 8 to 11 G; vertical, 8 to 10 G
- Horizontal displacement of head with respect to T1: 130 to 162 mm
- Downward displacement of head with respect to T1: 64 to 94 mm
- Time of maximum head excursion: 0.159 to 0.175 s

3.2.2.2 Requirements Based on Patrick and Chou Data

A rigid seat with a 15-degree seat back and 5-degree seat pan is securely fastened to a decelerator sled, sideward to the direction of travel. A vertical side board is attached to the seat to restrict torso and leg motion. The dummy is restrained by a lap belt and two shoulder belts which crisscross the chest. When the sled is subjected to a sled deceleration of 6.7 G from a sled velocity of 5.8 m/s, the dummy's responses must meet the following requirements:

- Angular rotation of head with respect to X-Z plane: 40 to 50 degrees
- Occipital condylar moment with respect to antero-posterior axis: 40 to 50 Nm
- Neck twist moment: 15 to 20 Nm
- Occipital condylar moment with respect to lateral axis: 20 to 30 Nm
- Lateral neck shear force at occipital condyles: 750 to 850 N
- Neck tension at occipital condyles: 350 to 400 N
- Fore/aft shear force at occipital condyles: 325 to 375 N
- Resultant head acceleration: 18 to 24 G

3.2.2.3 Requirements Based on APR Cadaver Tests

A rigid seat, similar to Ewing's seat, is mounted sideways on the sled. When the dummy is subjected to a velocity change of 22 km/h with an acceleration level of 12 G, its responses must satisfy the following requirements:

- Lateral acceleration of T1: 17 to 23 G
- Lateral head acceleration: 25 to 47 G
- Horizontal displacement of head with respect to sled: 185 to 226 mm
- Angular rotation of head with respect to X-Z plane: 62 to 75 degrees
- Head twist: 62 to 75 degrees

Note: Because of the lack of muscle tone in the cadavers, it may not be possible to meet both the human volunteer requirements and the cadaver requirements with a passive dummy neck design.

3.2.3 Lateral Thoracic Impact Requirements

The ISO has defined three sets of lateral thoracic impact response requirements based on the cadaver drop tests of APR [3.42], the cadaver sled tests of the University of Heidelberg [3.43] and the cadaver impact tests of the Highway Safety Research Institute (HSRI) [3.44]. All data sets were normalized to represent the response characteristics of a 50th-percentile, adult male using either the method developed by Mertz [3.45] or an extension of that method proposed by Lowne [3.46]. It should be noted that the ISO has decided to update the HSRI impact tests with the cadaver test results of Viano [3.47]. Only the revised [3.48] requirements are given for the impactor tests.

3.2.3.1 APR Drop Tests

The dummy, with its sagittal plane horizontal, is suspended over the impact surfaces using ropes to support its shoulder, hips and legs. Its arms are rotated forward and upward so that they do not contact the thoracic loading surface. Two loading surfaces are required to intercept the dummy's thorax and pelvis separately. For padded tests, 140 mm x 140 mm x 420 mm blocks of open-cell urethane foam are used. When the dummy is dropped onto the prescribed impact surfaces, its responses should meet the following requirements:

- For a 1-meter drop onto a rigid impact surface, the deflection of the impacted ribs relative to the mid-

sagittal plane of the thorax should be between 25 and 35 mm, and the thoracic impact force-vs.-time response should lie within the corridor shown in Figure 3-4 with the coordinates defined in Table 3-6

- For a 2-meter drop onto a padded impacted surface, the deflection of the impacted ribs relative to the mid-sagittal plane of the thorax should be between 38 and 48 mm, and the thoracic impact force-vs.-time response should lie within the corridor shown in Figure 3-4 with the coordinates defined in Table 3-6

3.2.3.2 Heidelberg Sled Tests

A rigid surface seat with two instrumented side panels is secured to an impact sled, sideways to the direction of travel. The side panels are located to intercept the thorax and pelvis of the dummy separately. In addition, they are mounted to load cells so that the thoracic and pelvic loads can be measured. The seat surfaces must have a low friction coefficient so that the dummy will translate relative to the seat without rotating. The dummy is positioned on the seat, far enough from the side panels, so that the sled acceleration will have been completed before the dummy impacts the side panels. For padded tests, 140 mm x 140 mm x 420 mm open-cell, urethane foam blocks are fastened to the panels supporting the thorax and pelvis. When the dummy impacts the side panels with the prescribed velocity, its responses should meet the following requirements:

- For a 6.8-m/s impact to rigid panels, the thoracic force-vs.-time response should lie within the corridor shown in Figure 3-4 with the coordinates defined in Table 3-6
- For a 8.9-m/s impact to rigid panels, the thoracic force-vs.-time response should lie within the corridor shown in Figure 3-4 with the coordinates defined in Table 3-6
- For a 8.9-m/s impact to padded panels, the thoracic force-vs.-time response should lie within the corridor shown in Figure 3-4 with the coordinates defined in Table 3-6

3.2.3.3 Impactor Tests of HSRI and Viano

The dummy is seated in an upright position with one arm raised so that the lateral aspect of its thorax can be impacted. A 23.4-kg impactor with a 150-mm diameter, flat and rigid impact surface is used to strike the dummy. For a 4.3-m/s impact, the impactor force-vs.-time curve should lie within the corridor shown in Figure 3-5 with the coordinates defined in Table 3-7, and the dummy's lateral thoracic spine acceleration of T1 should lie within the corridor shown in Figure 3-6. For a 6.7-m/s impact, the impactor force-vs.-time curve should lie within the corridor shown in Figure 3-5 with the coordinates defined in Table 3-7.

3.2.4 Lateral Shoulder Impact Requirement

The ISO has defined a response requirement for lateral loading of the shoulder [3.22] based on the results of cadaver impact tests conducted by APR [3.49]. A second set of shoulder response requirements has been proposed by Irwin [3.50], but has not been reviewed yet by WG5 and, therefore, will not be given.

3.2.4.1 APR Shoulder Impactor

The dummy is seated in an upright position with its arm angled forward as if supported by an armrest. A 23-kg, rigid, 150-mm diameter cylinder with a flat, unpadded face is used to strike the shoulder laterally at a velocity of 4.5 m/s. The cylindrical axis of the impactor is aligned with the center of the shoulder at impact. For a biofidelic response, the impactor force-vs.-time curve must lie within the corridor shown in Figure 3-5 with coordinates defined in Table 3-7, and the maximum deflection of the shoulder must lie between 34 and 41 mm.

3.2.5 Lateral Abdominal Impact Requirements

The ISO has defined a set of abdominal lateral impact requirements [3.23] based on cadaver drop tests on a simulated armrest conducted by APR [3.49 & 3.50]. The dummy, with its sagittal plane horizontal, is to be suspended over the impact surface using ropes to support its shoulder, hips and legs. A simulated armrest, constructed of rigid hardwood with a width of 70 mm, height of 41mm and sufficient length to assure that the dummy does not strike either end, is positioned to intercept the abdominal region in the area of the "9th rib" (R9). For a 1-meter drop, the force-vs.-time curve of the armrest should lie within the corridor shown in Figure 3-5 with coordinates defined in Table 3-7. The corresponding peak lateral accelerations of the twelfth thoracic vertebra (T12) and of the impacted rib should lie between 29 and 35 G, and 100 and 125 G, respectively. For a 2-meter drop, the armrest force should lie within the corridor shown in Figure 3-5 with coordinates defined in Table 3-7. The associated peak lateral accelerations of T12 and R9 should lie between 75 and 91 G, and 160 and 200 G, respectively.

Table 3-6
Coordinates for Biomechanical Response Corridors
for Various Thoracic Impact Conditions

Corridor Description		1 Meter Drop Rigid Surface		2 Meter Drop Padded Surface		6.8 m/s Rigid Wall		8.9 m/s Rigid Wall		8.9 m/s Padded Wall	
		Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)
Upper Boundary Coordinates	A	0	1.0	0	1.0	0	2.0	0	2.0	0	2.0
	B	16	7.0	10	10.5	16	9.0	12	13.5	26	12.5
	C	26	7.0	26	10.5	34	9.0	31	13.5	37	12.5
	D	43	2.0	45	2.0	54	2.0	51	2.0	60	3.0
Lower Boundary Coordinates	E	3	0.0	2	0.0	5	0.0	6	0.0	6	0.0
	F	21	5.8	18	8.2	24	7.2	21	11.0	31	9.5
	G	33	2.0	35	2.0	43	2.0	40	2.0	48	3.0

Table 3-7
Coordinates for Biomechanical Corridors
for Various Thoracic and Abdominal Impact Conditions

Corridor Description		4.3 m/s Chest Impact		6.7 m/s Chest Impact		4.5 m/s Shoulder Impact		1 Meter Drop Abdominal Impact		2 Meter Drop Abdominal Impact	
		Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)	Time (ms)	Force (kN)
Upper Boundary Coordinates	A	0	1.8	0	1.2	0	1.6	0	1.2	0	1.3
	B	10	3.7	5	5.2	5	2.8	13	4.4	8	6.1
	C	30	3.7	25	5.2	25	2.8	19	4.4	16	6.1
	D	45	2.0	45	2.5	58	1.0	38	1.0	38	0.5
Lower Boundary Coordinates	E	0	0.0	0	0.0	0	0.0	3	0.0	0	0.0
	F	10	1.7	15	3.2	13	1.7	17	2.5	14	4.1
	G	30	1.7	25	3.2	13	1.7	17	2.5	14	4.1
	H	40	0.0	45	0.0	42	0.6	32	0.5	27	0.5

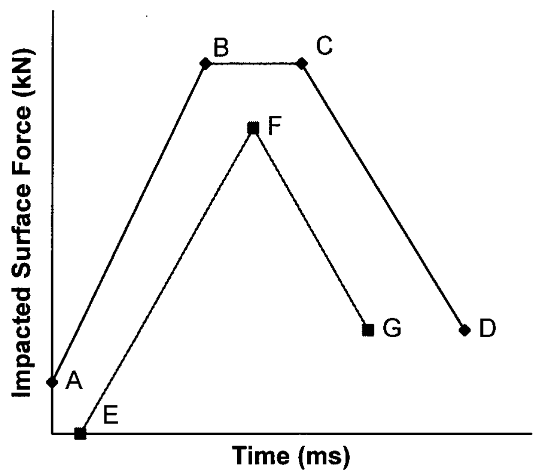

Figure 3-4
Biomechanical Response Corridor
for Various Thoracic Impact Conditions

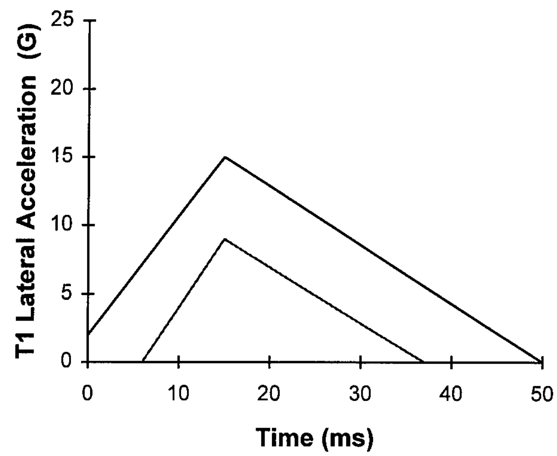

Figure 3-6
Normalized T1
Lateral Acceleration Response Corridor
for 4.3 m/s Chest Impact

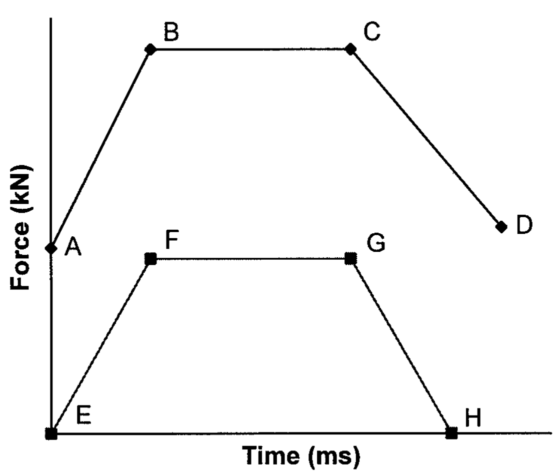

Figure 3-5
Biomechanical Response Corridor
for Various Thoracic and Abdominal
Impact Conditions
See Table 3-7 for Coordinates

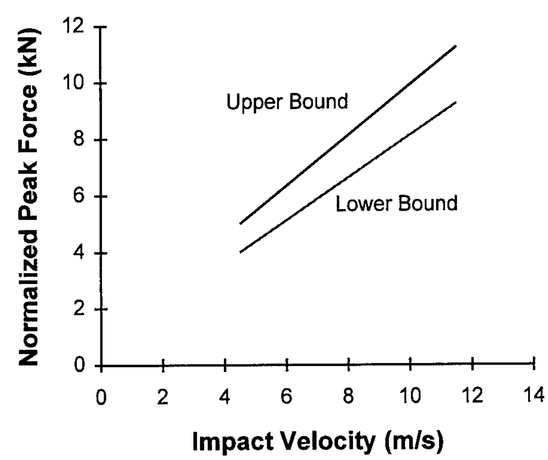

Figure 3-7
Biomechanical Response Corridor
for a 17.3 kg Rigid Impactor
Striking the Greater Trochanter Region

3.2.6 Lateral Pelvic Impact Requirements

The ISO has defined three sets of lateral pelvic impact response requirements [3.24] based on the cadaver impact tests conducted by Cesari et al. [3.52 to 3.54], the free-fall cadaver tests of APR [3.49] and the sled tests of the University of Heidelberg [3.43].

3.2.6.1 Impactor Tests of Cesari et al.

A rigid, 17.3-kg cylindrical impactor with a radius of 175 mm and a spherical segment face with a radius of 600 mm is used to strike an upright, seated dummy. The cylindrical axis of the impactor is aligned to strike the region of the greater trochanter (H-point) at velocities between 6 to 10 m/s. For a biofidelic response, the peak normalized [3.45] impactor force should lie within the corridor shown in Figure 3-7.

3.2.6.2 APR Drop Tests

The test setup here is the same as that described for the APR drop tests for the lateral thoracic impactor requirements. For a biofidelic response, the peak normalized [3.45] pelvic acceleration and peak normalized [3.45] pelvic impact force should lie within their respective ranges specified in Table 3-8.

3.2.6.3 Heidelberg Sled Tests

The test setup is the same as described for the Heidelberg sled tests for the lateral thoracic impact requirements. For a biofidelic response, the peak normalized [3.45] pelvic acceleration and peak normalized [3.45] impact force should lie within their respective ranges specified in Table 3-9.

3.3 ADVANCED DYNAMIC ANTHROPOMORPHIC MANIKIN (ADAM)

ADAM was developed for use in the evaluation of high-speed-aircraft ejection seat technology by SRL for the USAF Armstrong Laboratory (AL) [3.55 to 3.57]. While specifications were developed for three sizes of the manikin, only the large and small dummies were fabricated. The anthropometry of these manikins and the population used to develop the anthropometry are described in Chapter 4.

Table 3-8
Biofidelic Response Requirements
for Peak Normalized Pelvic Acceleration [3.24]

Drop Height (m)	Impact Surface	Peak Normalized Acceleration Bounds	
		Lower (G)	Upper (G)
0.5	Rigid	37	45
1.0	Rigid	63	77
2	APR Pad	39	47
3	APR Pad	48	58

Table 3-9
Biofidelic Response Requirements
for Peak Normalized Pelvic Acceleration
and Peak Normalized Impact Force [3.24]

Impact Velocity (km/h)	Impact Surface	Normalized Peak Pelvic Acceleration		Normalized Peak Impact Force	
		Lower (G)	Upper (G)	Lower (kN)	Upper (kN)
23.5	Rigid	63	77	6.4	7.8
32	Rigid	96	116	22.4	26.4
32	APR Pad	61	75	11.6	13.6

3.3.1 Range of Motion of Joints

There are 43 degrees of freedom designed into the joints of ADAM. Table 3-10 contains a partial listing of these degrees of freedom as well as the biofidelic requirements for the range of motion. Some of the range-of-motion data and characteristics for joint stops were taken from Engin [3.58]. A typical curve for elbow resistive forces is shown in Figure 3-8.

3.3.2 Spinal Response Requirements

To provide a human-like response to impulse loading in the vertical direction, ADAM was designed with a spring-damper unit that possesses the dynamic response of the lumbar and thoracic spine [3.59]. Figure 3-9 shows the predicted response of the ADAM design compared to the chest G_Z response of a human volunteer exposed to a vertical impulse of 12 G. Vibration tests from 3 Hz to 30 Hz at peak G_Z levels of ± 0.4 G and from 30 Hz to 200 Hz at peak G_Z levels of ± 1 G were conducted, but no human response targets were specified [3.55].

3.3.3 Durability Requirements

The impact durability requirements for ADAM are shown in Table 3-11. Testing to these and lower levels, and comparison to human responses in the vertical direction have been conducted by Buhrman [3.60] and in the horizontal direction by Strzelecki [3.61].

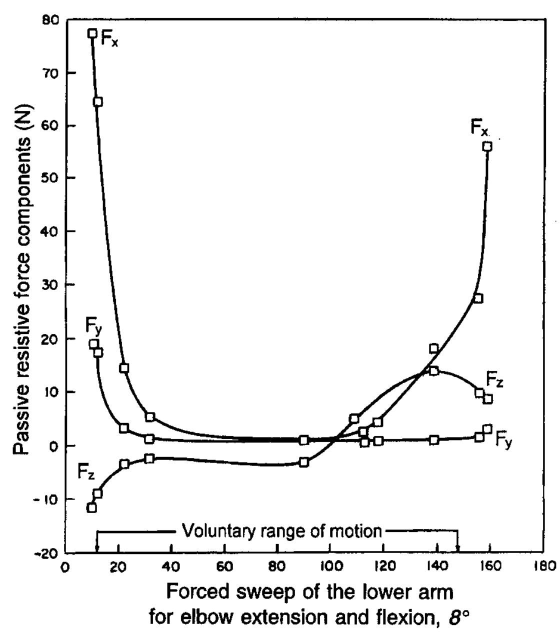

Figure 3-8
Elbow Resistive Force
Versus Rotation Angle [3.55]

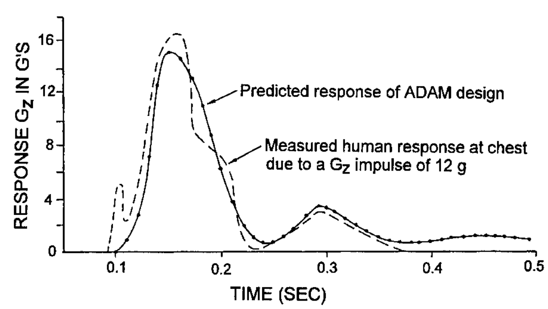

Figure 3-9
Comparison of Predicted
and Measured Response to G_Z

Table 3-10
Joint Degrees of Freedom and Rotation Limits [3.56]

Joint	Description of Motion	Angular Motion (Degrees)
Wrist	Flexion	85
	Extension	85
	Abduction	45
	Adduction	25
Elbow	Flexion	140
Forearm	Supination	95
	Pronation	75
Shoulder	Flexion	179
	Extension	57
	Abduction (Traverse Plane)	134
	Adduction (Traverse Plane)	48
	Abduction (Frontal Plane)	170
Sternoclavicular Joint	Pronation	10
	Retraction	10
	Elevation	10
	Depression	10
Upper Arm Rotations	Internal	115
	External	15
Ankle	Flexion	45
	Extension	25
	Inversion	34
	Eversion	18
Knee	Standing Flexion	125
	Tibial Rotation at 90° Flexion	
	Internal	35
	External	45
	Tibial Rotation at 0° Flexion	
	Internal	0
	External	0
Hip	Flexion	115
	Extension	0
	Supine Abduction	60
	Supine Adduction	30
	90° Flexion Abduction	50
	90° Flexion Adduction	30
	Rotation at 90° Flexion	
	Internal	40
	External	40
	Rotation at Full Extension	
	Internal	40
	External	40
	Rotation, Prone, knee at 90°	
	Internal	40
	External	40

Table 3-11
Acceleration and Impact Durability Tests [3.55]

Type of Test	G Level	Pulse Shape	Duration	Orientation
Acceleration	45	1/2 Sine Wave	120 ms	± Gx
Acceleration	45	1/2 Sine Wave	120 ms	± Gy
Acceleration	45	1/2 Sine Wave	120 ms	± Gz
Acceleration	100	1/2 Sine Wave	6 ms	± Gx
Acceleration	100	1/2 Sine Wave	6 ms	± Gz
Acceleration	30	1/2 Sine Wave	20 ms	± Gx

Chapter 4

Anthropometry: Current Adult Dummies

4.1 INTRODUCTION

Usually, each dummy is designed to represent a particular population. Ideally, that population will be the one that is expected to experience the environment in which the dummy is to be tested. For example, the Advanced Dynamic Anthropomorphic Manikin (ADAM) was designed to represent the military flying population of the United States [4.1], because it was to be used in testing USAF ejection seats. Dummy designs are also affected by their planned application objectives; i.e., whether the dummy is to be used as a test device to assess injury likelihood or to test the operation of protective systems. Dummies are usually designed to the anthropometry of an "average" person of the chosen population or to specific extremes in the body dimensions and masses of the population. The standard Hybrid dummies are designed primarily for safety standard qualifications testing, representing a 50th-percentile adult based on anthropometry derived by Hertzberg [4.2]. The rationale for this approach is that if an automobile protects an average individual, then a large percentage of the population would also be protected. This is the principal objective in safety standards testing. Most of the side impact dummies are also designed primarily for standards testing. The objective for other dummies is to test the operation of ejection seats, restraint systems and other protective devices at extreme conditions. If they do operate at the extreme conditions, then it is assumed that they will function over the full, small-to-large, population range. The small and large ADAM, 5th- and 95th-percentile Hybrid III, and the Joint Primary Aircraft Training System (JPATS) (see Chapter 7) dummies are examples of this design philosophy.

4.2 ANTHROPOMETRIC MEASUREMENTS

Table 4-1 lists some basic anthropometric measurements for current dummies. Body mass is determined with standard instrumentation. Several dummies have been designed in a seated position and the stature cannot be measured directly. An attempt has been made to identify the population on which the dummies are based by citing a reference to the anthropometric survey or report. The dimensions in the table were obtained from the references listed in the column: Data Source. Many of these references contain more detailed anthropometric data, joint range of motion, and other design criteria.

4.3 MASS PROPERTIES

Besides anthropometric dimensions, the mass properties of the dummies and their individual body segments are important in impact testing. The mass properties have a significant effect on the dynamics of the dummy. This is especially important in ejection seat testing, where the occupant's motion and center of mass affect the seat trajectory and stability. Table 4-2 contains the segmental masses of the current dummies on which data were available. The Hybrid III mass properties are from Kaleps and Whitestone [4.13] and the ADAM properties are from Rizer et al. [4.14]. Data regarding moments of inertia of the manikins are also available in the same references.

4.4 CONCLUSION

The anthropometric data for test manikins are important for two primary uses. The first is for understanding what the dummy represents, as described earlier. This should affect the choice of dummies used for a test program and the specifications for the design of a new dummy. Many of the currently-used dummies are based on population surveys conducted in the 1950s and 1960s. Since then, numerous surveys on various military and civilian populations have been conducted. Some of the most recent, comprehensive surveys are Ignazi's survey of the French military [4.15], the 1988 US Army Survey (ANSUR) [4.16], Stewart's survey of Canadian aircrew [4.17], a British Army survey conducted in 1974-1976 [4.18], two Royal Air Force Surveys in 1971-1972 [4.19 & 4.20], and the survey by Jurgens et al. of German men of age 25-40 years [4.21]. Also, AGARD/AMP Working Group 20 on 3-D Surface Anthropometry is currently preparing recommendations for future anthropometric surveys on body surface data. These surveys should be used in future designs to provide dummies that represent up-to-date applicable populations. The second primary use of the anthropometric data is in computer simulations as described in Chapter 8. These data are required input for computer models when simulating dummy dynamics.

Table 4-1
General Body Dimensions (m)

Dummy Type	Mass (kg)	Stature	Sitting Height	Buttock to Knee Length	Knee Height Sitting	Shoulder Height Sitting	Reference Population	Data Source
GARD/CG								
CG-5	60.1	1.656	0.858	0.556	0.510	0.542	[4.3]	
CG-50	73.4	1.755	0.914	0.599	0.551	0.592	[4.3]	
CG-95	91.1	1.856	0.966	0.645	0.592	0.638	[4.3]	
Hybrid II								
50th Male	74.4	n/a[k]	0.907	0.592	0.544	0.599	Civilian male[d] [4.2]	[4.4]
Hybrid III								
5th Female	48.7	n/a[k]	0.790	0.521	0.457	0.442[b]	Civilian female [4.5]	[4.6]
50th Male	78.2	n/a[k]	0.884	0.592	0.493[g]	0.513[b]	Civilian male[d] [4.2 & 4.7]	[4.8]
95th Male	101.1	n/a[k]	0.935	0.633	0.594	0.549[b]	Civilian male [4.5]	[4.6]
Aerospace								
5th Female	49.0	1.483	0.800	0.544	0.465	0.508	Military female[c]	
5th Male	71.7	1.650	0.879	0.559	0.518	0.536	USAF flying personnel [4.9]	
50th Male	85.7	1.697	0.886	0.591	0.544	0.599	Civilian male[d] [4.2]	[4.4]
95th Male	98.0	1.864	0.991	0.688	0.635		Military male[c]	
ADAM								
Small	64.2[a]	1.683	0.876	0.564	0.538	0.597	Small male aviator [4.1]	[4.10]
Large	98.3[a]	1.886	0.953	0.654	0.603	0.663	Large male aviator [4.1]	[4.10]
SID								
50th Male	76.5	n/a[k]	0.899	0.592	0.544	n/a	Civilian male [4.5]	[4.4]
BIOSID								
50th Male	76.2	n/a[k]	0.884	0.592	0.493[g]	0.513	Civilian male [4.5]	[4.11]
EUROSID 1								
50th Male	72.0	n/a[k]	0.904	0.610	0.544	0.557[b]	Civilian male [4.5]	[4.12]

a - Mass with on-board data acquisition system
b - Shoulder pivot height sitting
c - SAE J963 [4.4] modified by military service data
d - Military data adjusted to represent civilian population
g - Knee pivot height
k - Standard dummies have pelvis molded in a seated position and cannot stand. Standing versions of Hybrid II and Hybrid III are available as a special order

Table 4-2
Manikin Segmental Masses (kg)

Segment	Hybrid III 50th [4.13]		ADAM [4.14]	
	Sitting	**Standing***	**Large**	**Small**
Head	4.50	4.50	4.33	4.20
Neck	1.21	1.21	1.37	1.04
Lower Torso	20.17	9.94	19.32	8.38
Middle Torso	2.22	1.21	-	-
Upper Torso	17.79	17.79	29.24	20.06
Upper Arm	2.09	2.09	2.40	1.62
Forearm	1.72	1.72	1.67	1.32
Hand	0.59	0.59	0.76	0.54
Thigh	6.22	9.06	12.02	7.78
Lower Leg	3.28	3.28	4.46	3.09
Foot	1.25	1.25	0.95	0.93
Total	**76.18**	**70.63**	**98.30**	**64.24**

* without ballast weight

Chapter 5

Injury Assessment

5.1 INJURY DISTRIBUTIONS

Over the past several decades, data have been collected to define the distributions of injury to crewmen in aircraft ejection and occupants in vehicle collisions. This information is needed for defining appropriate test conditions and dummy measurements for evaluating advanced escape and/or restraint systems.

5.1.1 Aircrew Escape Data

In 1992, Raddin et al. [5.1] compiled statistics for the period 1975 to 1991 of injuries experienced by crewmen while escaping from a variety of USAF aircraft. There were 126 fatalities among the 620 persons in the sample. The distribution of injuries experienced by the fatally injured crewmen are shown in Figure 5-1. Injuries to the head, lower extremities, thorax and neck were most prevelant. Among the 494 survivors, 100 crewmen had injuries considered as major. Figure 5-2 shows the distribution of injuries for the survivors. The thoracic and cervical spine are the most prominent regions affected. Injuries to the head and lower extremity were significantly less when compared to their occurrences when there were fatalities.

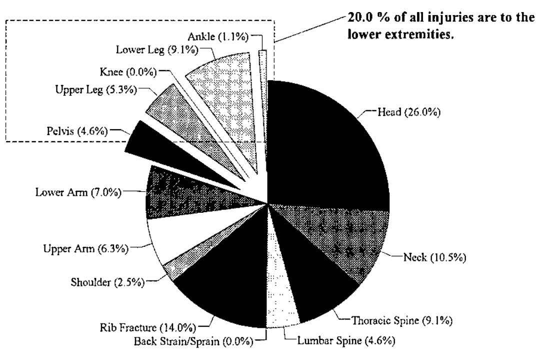

Figure 5-1
Distribution of Injuries in USAF Escape System Fatalities (1975-1991)
Data from Rabbin, J.H. et al. [5.1]

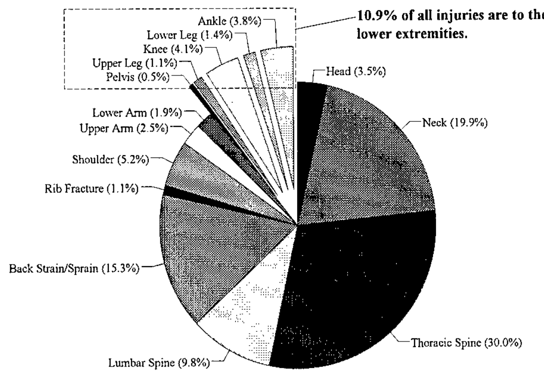

Figure 5-2
Distribution of Injuries in USAF Escape System Survivors (1975-1991)
Data from Rabbin, J.H. et al. [5.1]

5.1.2 Aircraft Crash Data

Shanahan and Shanahan [5.2] reported injury patterns and mechanisms in US Army helicopter crashes over the period from 1980 to 1985. Among 1060 occupants aboard helicopters involved in major accidents in this six year period, 611 were injured, including 136 that were fatal. The distribution of major/fatal injuries by body region in survivable crashes is presented in Figure 5-3. The army classified a crash as "survivable" if the forces at impact were considered to be within the limits of human tolerance, and if the occupied volume was sufficiently maintained throughout the crash sequence to permit occupant survival in all potentially occupied positions. A fatal injury was one that resulted in death, whereas a major injury was one that did not result in death but resulted in the loss of a workday or required the individual to be placed on restricted work activity. Figure 5-3 indicates that the head has the highest frequency of major/fatal injuries.

5.1.3 Automotive Crash Data

The National Accident Sampling System (NASS) was developed by the US National Highway Traffic Safety Administration (NHTSA) to provide estimates of the distributions of injuries to occupants involved in

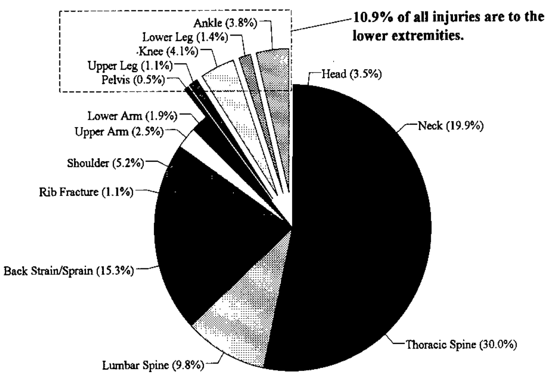

Figure 5-3
Distribution of Major Fatal Injuries in Survivable US Army Helicopter Crashes (1980-1985) (Data from Shanahan, D.F. and Shanahan, M.O. [5.2]

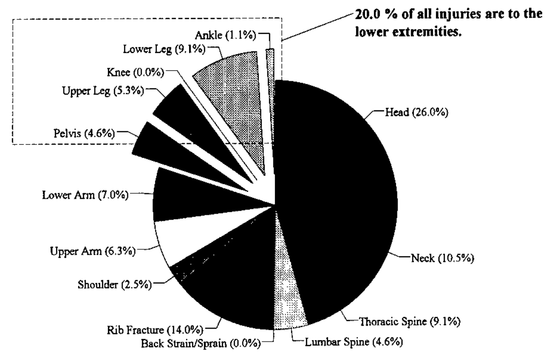

Figure 5-4
Distribution of Automotive Injuries AIS ≥ 2 (1979-1986)
Belted Occupants in Frontal Crashes [5.3]

vehicle accidents [5.3]. Comparable data sources are also found in Europe. These are at Laboratoire d'Accidentologie et Biomecanique (LAB) and Institut National de Recherche sur les Transport et leur Securite (INRETS) in France; Accident Research Unit, University of Birmingham, and Transport Research Laboratory (TRL) in the United Kingdom; and the Universities of Heidelberg and Hanover, and Bundesanstalt fuer Strassenvessen Bergisch Gladbach (BAST) in Germany. Car manufacturers also have their own accident investigation laboratories.

The severities of injuries associated with automotive accidents are classified according to the Abbreviated Injury Scale (AIS) developed by the Association for Advancement of Automotive Medicine [5.4]. Table 5-1 gives the descriptions of the injury severity associated with the various AIS classifications.

Table 5-1
Abbreviated Injury Scale (AIS) [5.4]

AIS	Severity of Injury
0	Not Injured
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum
7	Injured but Severity Not Known

Figure 5-4 shows the distribution of AIS $\geq$ 2 injuries for belted occupants involved in frontal accidents based on NASS data for the period of 1979-86. The most frequent injuries were to the head/face, lower extremity and thorax. Since the sample period is for 1979-86, the influence of air bags is not reflected in the injury distribution shown in Figure 5-4.

5.2 INJURY ASSESSMENT REFERENCE VALUES (IARVS)

Overall summaries of biomechanical data used to develop criteria for evaluating the efficacy of aircraft escape systems are given by Raddin et al. [5.1] and for evaluating automotive restraint systems by the Society of Automotive Engineers (SAE) Information Report J885 [5.5]. In 1984, General Motors Corporation (GM) made public a set of Injury Assessment Reference Values (IARVs) that they used as guidelines for assessing the injury potential associated with the various measurements made with the Hybrid III, 50th-percentile adult male dummy [5.6]. They noted that each IARV refers "to a human response level below which a specified significant injury is considered unlikely to occur for a given individual". However, they cautioned that being below all of the IARVs does not assure that significant injury would not occur. This is because IARVs are not specified for all injury types, and the dummy is not instrumented to measure the responses associated with all occupant injuries experienced in the simulated collision. Further, they noted that exceeding an IARV does not

Table 5-2
Injury Assessment Reference Values for (IARVs) Hybrid III Type Adult Dummies [5.7]

Body Region **Injury Assessment Criteria**	**Small Female**	**Mid-Size Male**	**Large Male**
Head			
HIC; $(t_2 - t_1) \leq 15$ ms	1113	1000	957
Head/Neck Interface			
Flexion Bending Moment (Nm)	104	190	258
Extension Bending Moment (Nm)	31	57	78
Axial Tension (N)	Fig. 5.5	Fig. 5.5	Fig. 5.5
Axial Compression (N)	Fig. 5.6	Fig. 5.6	Fig. 5.6
Fore/Aft Shear (N)	Fig. 5.7	Fig. 5.7	Fig. 5.7
Chest			
Spinal Acceleration (G)	73	60	54
Sternal Deflection due to:			
Shoulder Belt (mm)	41	50	55
Air Bag & Steering Wheel Hub (mm)	53	65	72
Viscous Criterion (V*C) (m/s)	1	1	1
Femur			
Axial Compression (N)	Fig. 5.8	Fig. 5.8	Fig. 5.8
Knee			
Tibia-to-Femur Translation (mm)	12	15	17
Med./Lat. Clevis Compression (N)	2552	4000	4920
Tibia			
Axial Compression (N)	5104	8000	9840
Tibia Index, $TI = M/M_c + F/F_c$	1	1	1
where,			
M_c - Critical Bending Moment (Nm)	115	225	307
F_c - Critical Comp. Force (kN)	22.9	35.9	44.2

necessarily imply that a person would be injured if exposed to the collision being simulated since the IARVs are not injury thresholds.

5.2.1 IARVs for Frontal Impact Dummies

In 1993, Mertz [5.7] published an updated version of the IARVs for the various dummies used by GM in their automotive restraint system testing. Table 5-2 gives the IARVs for the head, neck, chest and lower extremities for the small female, mid-size male and large male, Hybrid III type dummies. Note that the IARVs for neck tension, compression and shear, and femur compression are given by time dependent criteria which are shown in Figures 5-5 to 5-8, respectively. The abscissas of these curves are the duration that a given load level is exceeded on a continuous basis.

The biomechanical basis for the mid-size male IARVs is given in References [5.8] through [5.36]. The corresponding IARVs for the small female and large male were scaled from the mid-size male values using the geometric and inertial scale factors given by Mertz and Irwin [5.37], and assuming that failure stress is independent of size differences.

The Head Injury Criterion (HIC) [5.5] is defined as:

$$HIC = (A_{avg})^{2.5} (t_2 - t_1)$$

where A_{avg} is the average resultant acceleration of the center of mass of the head (expressed in G) for the time interval $t_2 - t_1$ (expressed in seconds) which gives the maximum HIC value. The Federal Motor Vehicle Safety Standard (FMVSS) 208 of the United States limits the maximal time interval to 36 ms. This time

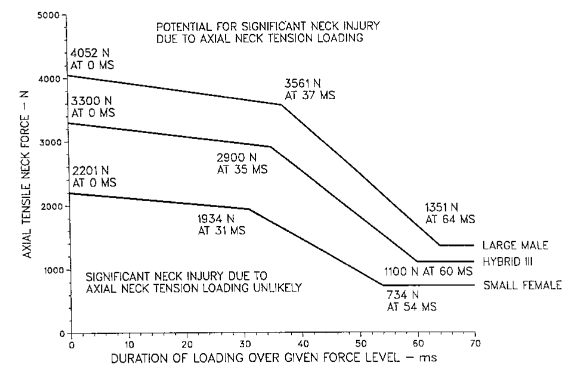

Figure 5-5
Injury Assessment Curves for Axial Neck Tension
Measured with Hybrid III Type Adult Dummies [5.7]

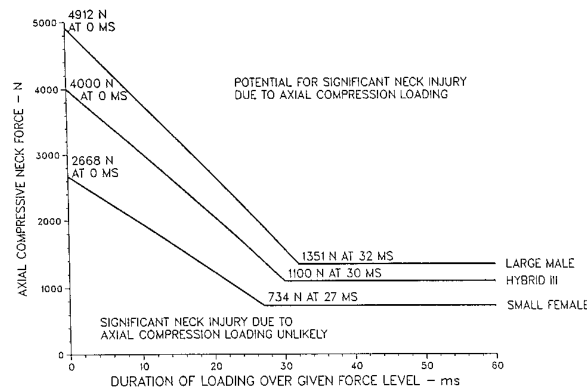

Figure 5-6
Injury Assessment Curves for Axial Neck Compression
Measured with Hybrid III Type Adult Dummies [5.7]

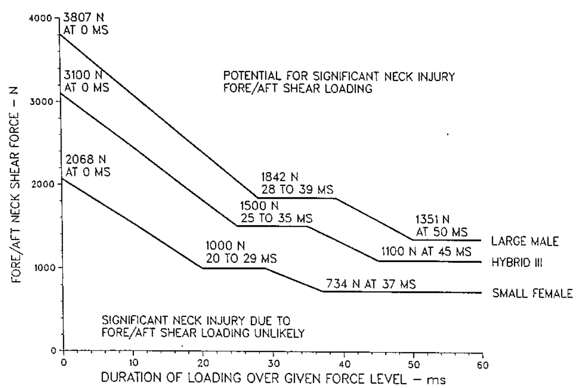

Figure 5-7
Injury Assessment Curves for Fore-and-Aft Sheer
Forces Measured at the Head/Neck Interface
of Hybrid III Type Adult Dummies [5.7]

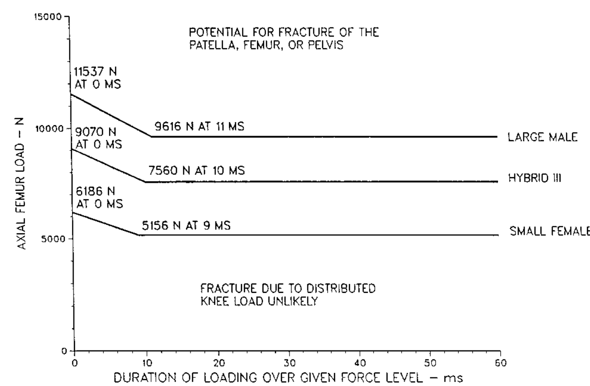

Figure 5-8
Injury Assessment Curves for Axial Compressive
Femur Force Measured with Hybrid III
Type Adult Dummies [5.7]

interval limit is too large since it results in unrealistically high HIC values for air-bag interactions and three-point restraint system testing without having head contact with the vehicle interior. Both of these conditions have a low risk of causing brain injury. To address this concern, the International Organization for Standardization (ISO) has opted to limit the search for the maximal HIC value to 15 ms or less, which is consistent with the available biomechanical data for head impact [5.8] and is the constraint given in Table 5-2.

FMVSS 208 limits the HIC to 1000, the 3-ms resultant chest acceleration to 60 G, the chest compression to 3 inches (76 mm) and the axial compressive femur loads to 2250 pounds (10 kN). For FMVSS 208, the search for the maximal HIC value is limited to a HIC duration of 36 ms or less.

The Viscous Criterion (V*C) [5.25 and 5.26] is defined as:

$$V * C = 1.3\, V\, (\delta / D)$$

where V is the rate of chest compression (expressed in m/s), δ is the sternal deflection and D is the chest depth. The values of D used for the small female, mid-size male and large male, Hybrid III type dummies are 187 mm, 229 mm and 254 mm, respectively.

Injury risk curves have been proposed for HIC [5.8] and sternal deflection due to shoulder belt loading [5.20 to 5.22], and are shown in Figures 5-9 and 5-10, respectively. Note that to use the head injury risk curve of Figure 5-9 or the HIC IARV of Table 5-2, the search for the maximal HIC value must be limited to HIC durations of 15 ms or less.

To assess the potential for facial lacerations from windshield glass, the head of the dummy is covered with two layers of chamois. Cuts to the chamois are evaluated using the Corning Scale [5.38] given in Table 5-3. It should be noted that with the mandatory use of air bags in the United States, facial laceration from windshield contact is no longer a concern.

5.2.2 IARVs for Side Impact Dummies

A summary of the IARVs proposed for the three side impact dummies; SID, EUROSID 1 and BIOSID are given in Table 5-4. The biomechanical basis for these IARVs are given in References [5.39] and [5.40]. These IARVs are quite tentative since no field data are available yet to assess the efficacy of the side impact protective systems that have been designed to meet these IARVs. The limits required by FMVSS 214 for SID and proposed by Economic Commission of Europe (ECE) R95 for EUROSID 1 are indicated.

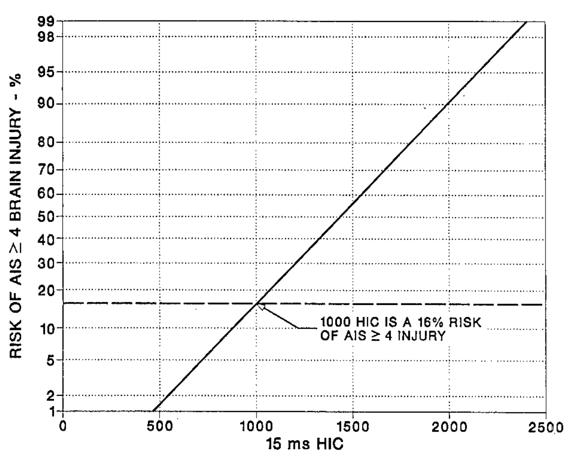

Figure 5-9
Risk of AIS $\geq$ 4 Brain Injury as a Function of 15-ms HIC [5.7 & 5.8]

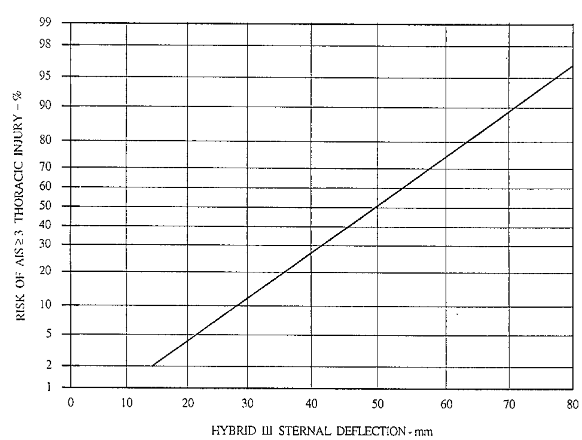

Figure 5-10
Risk of AIS $\geq$ 3 Thoracic Injury Due to Shoulder Belt Loading as a Function of Hybrid III Sternal Deflection [5.20 to 5.22]

Table 5-3
Corning Scale for Facial Laceration [5.38]

Degree		Outer Chamois	Inner Chamois	Rubber Dummy Face
0	None	None	None	None
1	Minimal	Abrasions. Cuts of 3/4 inch - none through	None	None
2	Minor	Abrasions. Cuts over 3/4 inch - none through	None	None
3	Minor	As Degree 2, but one cut through	Abrasion	None
4	Moderate	Two or three cuts through	Cuts, but not through	None
5	Moderate	Unlimited cuts	Two or three cuts through up to 1/2 inch	None
7	Severe	Unlimited cuts	Unlimited cuts	Abrasions
8	Severe	Unlimited cuts	Unlimited cuts	Cuts up to 1/32 inch deep and 3/4 inch long
9	Very Severe	Unlimited cuts	Unlimited cuts	One cut deeper or longer than Degree 8
10	Very Severe	Unlimited cuts	Unlimited cuts	Numerous cuts worse than Degree 9

Table 5-4
Injury Assessment Reference Values (IARVs) for Side Impact Dummy Measurements [5.7]

Body Region Injury Assessment Criteria	SID *	EUROSID 1	BIOSID
Head			
HIC; $(t_2 - t_1) \leq$ 15 ms	-	-	1000
HIC; $(t_2 - t_2) \leq$ 36 ms	-	1000 **	-
Chest			
Lat. Rib-to-Spine Def. (mm)	-	42 **	42
Thoracic Trauma Index (TTI)			
Coupe (G)	90	90	90
Sedan (G)	85	85	85
Viscous Criterion (V*C) (m/s)	-	1	1
Abdomen			
Lateral Compression (mm)	-	-	39
Lateral Force, Internal (kN)	-	2.5 **	-
Pelvis			
Lateral Acceleration (G)	130	130	130
Pubic Symphysis Force (kN)	-	6 **	6
Iliac Wing Force (kN)	-		6

* FMVSS 214 Limits
** Proposed ECE R95 Limits

The Thoracic Trauma Index (TTI) is calculated by averaging the maximal value of the lower thoracic spine acceleration and the maximal value of the greater value of the upper or lower rib lateral acceleration [5.39]. The Viscous Criterion for lateral impact is defined as:

$$V * C = V\,(\delta/D)$$

where V is the rate of lateral compression of the impacted ribs relative to the thoracic spine, δ is the corresponding lateral deflection of the rib, and D is the thoracic width. For BIOSID and EUROSID 1, the values of D are 175 mm and 140 mm, respectively.

5.3 SPINAL INJURY MODELS

Unlike the IARVs which use data measured on a dummy, the spinal injury criteria have been primarily based on measurements made on the ejection seat. They each analytically model the human body to transform the seat response into some indicative body response and resulting injury probability.

5.3.1 Dynamic Response Index (DRI)

The Dynamic Response Index (DRI) was developed to predict probability of thoracolumbar-spine fracture injury during ejection seat use [5.41 & 5.42]. The DRI uses a simple mass-spring-damper system for predicting the gross response of an aircrew member subjected to abrupt vertical acceleration. The equation of motion for this system is:

$$\ddot{\delta} + 2\zeta\omega_n\dot{\delta} + \omega_n^2\delta = a_c$$

where δ is the deflection of the system, ζ is the damping ratio, ω_n is the natural frequency, and a_c is the critical point acceleration in the vertical direction. The DRI is the square of the natural frequency of the system, ω_n multiplied by the maximal compressive deflection, δ_{max} that results from a +Z (foot-to-head) driving force or acceleration, and divided by the acceleration of gravity, G:

$$DRI = \frac{\omega_n^2\delta_{max}}{G}$$

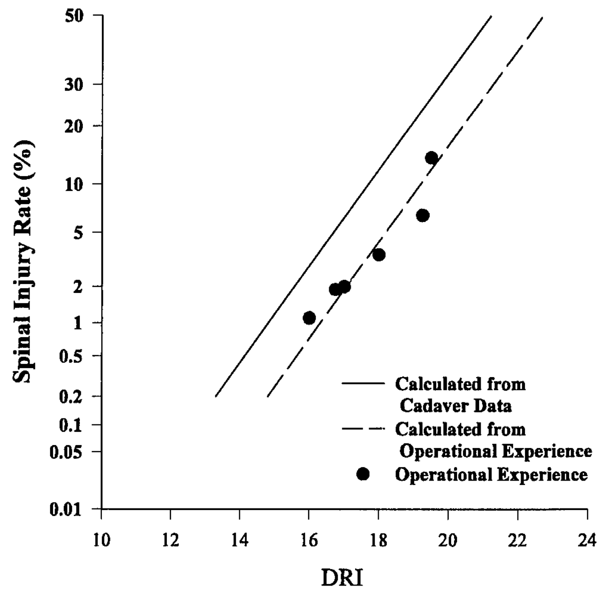

Figure 5-11
Probability of Spinal Injury
Estimated from Laboratory Data Compared to Operational Experience [5.42]

In the calculation of DRI, ω_n is 52.9 radians/s and ζ is 0.224. The DRI has been correlated to spinal injury data from laboratory and operational experience. Figure 5-11 shows the rate of spinal injury as a function of DRI.

5.3.2 Acceleration Exposure Limit Method

The Acceleration Exposure Limit Method was developed by expanding the DRI methodology to other axes [5.43]. This method predicts the probability of injury due to combined X, Y, and Z accelerations and angular velocities. The dynamic response (DR) and associated risk of injury are computed at a specific critical point. This point is typically the upper-torso center of mass. The linear accelerations at the critical point are calculated from the measured accelerations and angular velocities. The DR for each axis is calculated independently using the above equations of motion and DRI. The ω_n is 62.8 radians/s for the +X axis, 60.8 radians/s for -X, 58.0 radians/s for Y, 52.9 radians/s for +Z, and 47.1 radians/s for -Z. ζ is 0.2 for the +X axis, 0.04 for -X, 0.09 for Y, 0.224 for +Z, and 0.24 for -Z. The individual DR values are compared to DR limit values for low, medium, and high risks in Table 5-5 to determine the degree of risk for each axis.

The general risk of injury, β is calculated based on the DR values for the three axes and the corresponding DR limit values from Table 5-5. β is calculated using:

$$\beta = \sqrt{\left(\frac{DR_X}{DR_{X\text{limit}}}\right)^2 + \left(\frac{DR_Y}{DR_{Y\text{limit}}}\right)^2 + \left(\frac{DRZ_Z}{DR_{Z\text{limit}}}\right)^2}$$

where DR_i $(i=X, Y \text{ or } Z)$ is the dynamic response for the i-th axis, and $DR_{i\text{limit}}$ is its corresponding DR limit value. The occupant is considered to have exceeded the specified injury risk level if the injury risk criterion, β, is greater than one.

Table 5-5
DR Limit Values for Acceleration Exposure Limit Method [updated from 5.43]

Axes	DR Limit Value (G) Low	Medium	High
+X	35	40	46
-X	28	35	46
±Y w/side panels	15	20	30
±Y w/o side panels	14	17	22
+Z	15.2	18.0	22.8
-Z	13.4	16.5	20.4

5.4 MAXIMAL STRAIN CRITERION (MSC)

Another criterion used to predict head injury is the Maximal Strain Criterion (MSC) [5.44]. With this method, the head is modeled as a linear two degree-of-freedom system and injury is based on average strain across the brain, which is calculated using:

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = -a(t)$$

where m is the mass of the brain and non-parietal bones of the head, k is the skull stiffness, and c is the viscosity of the skin, muscle, and brain.

Stalnaker and McElhaney [5.44] provide values for these coefficients. $a(t)$ is the input acceleration of the parietal sections of the skull and x is the strain across the brain. This strain is normalized by dividing by the linear dimension of the brain in the impact direction (L_H) to obtain:

$$MSC = \frac{x}{L_H}$$

This allows the MSC criterion to be used for longitudinal and lateral head impacts. Phillips [5.45] defines injury levels associated with MSC values. For example, the no-injury limit in a human is an MSC of 0.0022, and the marginal level of irreversible injury is an MSC of 0.0061.

Chapter 6

Instrumentation and Data Acquisition

6.1 DATA ACQUISITION STANDARDS

Presently, two (2) data acquisition standards are used in the automotive industry;

- Society of Automotive Engineers (SAE) J211 March 1995, Instrumentation for Impact Test [6.1]
- International Organization for Standardization (ISO) 6487, Road Vehicles - Measurement Techniques in Impact Tests - Instrumentation [6.2]

The SAE standard was developed and is updated periodically by the Safety Test Instrumentation Standards Committee. The latest revision is March 1995. The ISO standard was developed and is currently being updated by the Working Group ISO/TC22/SC12/WG3 - Instrumentation. A draft version N294E [6.3] is in the balloting process.

The above committees are exchanging information and efforts are being made to harmonize the standards.

6.1.1 Purpose

The purpose of these standards is to set minimal guidelines to ensure accurate measurements of physical quantities during impact tests. These guidelines ensure uniformity in the data acquisition and processing of signals which is necessary for the comparison of test results between laboratories.

6.1.2 Description

The standards set accuracy tolerances on a series of parameters which apply to the complete data channel and include all instrumentation from the transducer to the recording system as well as any analog or digital processing applied to the signal. The standards provide definitions of the terminology used and state the accuracy tolerances for the following parameters:

- Linearity
- Amplitude vs. frequency
- Phase delay
- Time base
- Relative time delay
- Transducer transverse sensitivity

The accuracy of the reference equipment used to calibrate the data acquisition equipment is defined, as well as the ranges in which sensitivity, linearity and frequency response should be measured.

6.1.3 Recommendations for Uniformity

The standards also contain guidelines to ensure the uniformity of the data acquisition and processing such as filtering, choice of Channel Frequency Class (CFC), sign convention, recording, digital signal processing, and data exchange formats. Some of these items are discussed in more detail in the following paragraphs.

6.1.3.1 *Filtering*

To facilitate the analysis of data signals, by removing undesirable vibration components and/or electrical noise, filters having four different frequency responses are defined. The choice of one of these filters defines the CFC. The classes are designated CFC1000, CFC600, CFC180 and CFC60. The numbers in the classification correspond to the frequency at which the frequency response curve is between + 0.5 db and - 1.0 db. The filters are specified by corridors that set upper and lower amplitude limits into which the data-channel, frequency response curve must fall. The amplitude tolerances, in the lower frequencies, of the frequency response curves were set to cover various error sources in the data acquisition chain, mainly in the transducers. Well designed low-pass filters have a unity gain at low frequencies. The corridors in the roll-off region were set to permit a wide range of equipment and filter types. The wide corridors of the roll-off region were found to permit filters of sufficiently different responses to produce variations of peak values for the same input signal. The committees are presently working to narrow the corridors and/or to adopt a unique filter that would be defined by an algorithm. This will ensure uniform filtering. Ideal filter uniformity cannot be achieved easily for all filter classes. Many laboratories use analog anti-aliasing filters that are within the CFC1000 corridor for all data channels and use digital filters to bring specific channels to lower filter classes as necessary.

SAE J211 March 1995 specifies a narrower corridor for CFC1000 and CFC600 and also specifies the Butterworth digital filter algorithm described in its Appendix A for CFC180 and CFC60.

Table 6-1
Frequency Response Classes

Typical Test Measurements	Channel Frequency Class (CFC)
Anthropomorphic Test Dummy	
Head Accelerations (linear and angular)	1000
Neck	
Forces	1000
Moments	600
Thorax	
Spine Accelerations	180
Rib Accelerations	1000
Sternum Accelerations	1000
Deflections	600
Lumbar	
Forces	1000
Moments	1000
Pelvis	
Accelerations	1000
Forces	1000
Moments	1000
Femur/Knee/Tibia/Ankle	
Forces	600
Moments	600
Displacements	180
Sled Acceleration	60
Steering Column Loads	600
Headform Acceleration	1000

The "draft" version of ISO 6487 [6.3] specifies the same corridors for CFC1000 and CFC600 as the revised SAE J211. The corridors for CFC60 and CFC180 have also been narrowed; however, a digital filter algorithm is not required.

6.1.3.2 *Choice of CFC*

A table is provided in SAE J211 recommending the CFC to use when filtering signals from transducers located in the anthropomorphic test devices (ATDs) and on vehicle structures. This table has been developed from user experience and biomechanical considerations. Care has been taken to avoid attenuating valid signals and modifying the results of injury criteria by the filtering process. A part of the table is reproduced as Table 6-1. Users should refer to SAE J211 for complete details on the CFC requirements.

6.1.3.3 *Sign Convention*

To allow for the exchange of data and the establishment of test data bases, it has become increasingly important to have a sign convention which covers all of the transducers in the ATDs as well as the test vehicles. A section in SAE J211 March 1995 describes the sign convention and illustrates its use for sled and vehicle tests. SAE Information Report J1733, Sign Convention for Crash Testing [6.4] provides more comprehensive details of the sign convention for each body segment. The sign convention applies to forces, moments, accelerations and displacements. Illustrations of the SAE sign convention, for the standing and seated dummy postures, are presented in Figures 6-1 and 6-2.

The Committee on Acceleration of the Aerospace Medical Panel of AGARD published a paper entitled "Table of Equivalents for Acceleration Terminology", Aerospace Medicine, December 1961 [6.5]. The sign convention presented in this paper for the "direction of acceleration" is in agreement with that of SAE J1733.

ISO Document 8727, Biodynamic Coordinate Systems [6.6] describes anatomical and basicentric coordinate systems for biodynamical measurements for precisely

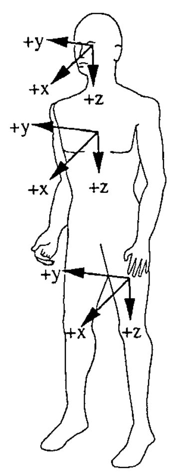

Figure 6-1
SAE Dummy Coordinate System
Standing Posture

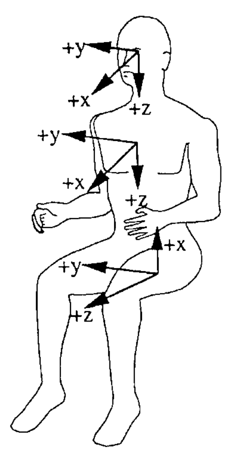

Figure 6-2
SAE Dummy Coordinate System
Seated Posture

describing human exposure to mechanical vibration and shock. The segmental anatomical coordinate systems defined are for the head, base of neck, pelvis and hand.

6.1.3.4 *Recording*

Both the SAE and ISO standards contain recommendations for proper analog and digital data recording techniques for analogue magnetic, digital magnetic and paper tape recorders.

6.1.3.5 *Digital Data Processing*

Presample filtering, minimum sampling rates and resolution accuracy have been harmonized. Differences in computational techniques for injury criteria have been noted in different laboratories. This has led to the preparation of the SAE Information Report J1727, Injury Calculation Guidelines [6.7] which describes recommended techniques for computing the various injury criteria. This Information Report is referenced in SAE J211 March 1995.

6.1.3.6 *Data Exchange Format*

For the purpose of exchanging test data in digital form, SAE J211 March 1995 recommends the use of the National Highway Traffic Safety Administration (NHTSA) "Formats for Data Exchange" [6.8]. This is a very comprehensive series of formats not only providing a format to exchange data channels, but including information on test conditions such as velocity, angle of travel, impact point of vehicles, vehicle description, pre- and post-test dimensions, ATDs with specifications and positioning documentation, transducer location, sensitivity, orientation, last calibration date, etc. The documentation for this format can be obtained, for a nominal fee, through the Office of Crashworthiness Research (NHTSA), 400 7th Street S.W. NRD-12, Washington, D.C. 20590-0002. The title of the documentation is NHTSA Data Tape Reference Guide (Version 4): Volume 1 - Vehicle Tests; Volume 2 - Biomechanics; Volume 3 - Components; Volume 4 - Signal Waveform Generator.

A "draft"proposal has been issued by ISO/TC22/SC12/ WG3 N300 [6.9] for a different data exchange standard.

6.1.4 **Photographic Instrumentation**

SAE J211 March 1995 contains a section for photographic instrumentation which defines performance criteria to evaluate optical data acquisition

and analysis systems such as high speed photography. It defines the criteria of performance for an optical data channel when numerical time and space data are taken from the images to analyze the test results.

6.2 SENSORS FOR DUMMY TESTING

Sensors normally used to measure the responses of the ATDs can be classified into three (3) basic categories; acceleration, force and displacement/position. Pressure and temperature sensors are also used depending on the type of testing that is to be performed.

Within each category there may be several sensor types such as linear and angular accelerometers, shear, axial and torque load cells, linear and rotary potentiometers, etc. Within each type there may be different classes such as piezoelectric, piezoresistive, variable capacitance and internal electronics accelerometers as well as piezoelectric and strain-gage type load cells. Other types include optical displacement and angular rate sensors.

For many of the sensor types, there may be more than one manufacturer. Each manufacturer has its own specifications; therefore, there may be significant differences between sensors designed by different manufacturers for the same type of measurement. Careful consideration should be given to ensure that each sensor is suitable for the requirements of the specific application.

In the design and development of some of the dummies, a specific sensor model and/or manufacturer has sometimes been included on the drawings. In cases where these drawings have been incorporated into a US Federal Regulation, the words "or equivalent" have been added after the sensor model number. SAE J211 March 1995 has included a section which addresses "transducer equivalency".

It should be noted that other types of devices and/or techniques have been developed for special applications and/or evaluations. Some of these devices are passive and do not provide an electronic output signal while others utilize a grouping of sensors such as strain gages, load cells, accelerometers, etc. to provide data from a body segment. Examples of passive sensing devices are the deformable abdominal insert [6.10 & 6.11] developed to provide physical evidence of submarining and the frangible face form [6.12] to monitor facial bone fractures during automotive crash tests. Examples of active sensors grouped together for special measurements are the Deformable Load Sensing Hybrid III Face [6.13] and the Lateral Load Sensing Hybrid III Head [6.14]. These devices utilize load cells to provide data from the various sections of the head.

The following paragraphs describe the types of sensors typically used in the dummies and the body segments in which they are normally located. Tables 6-2 and 6-3 provide a listing of the instrumentation that is available for the adult escape system and frontal impact dummies, and the adult side impact dummies. Figures 6-3 and 6-4 are illustrations of the sensor locations for the ADAM and Hybrid III adult dummies. Figures 6-5, 6-6 and 6-7 are illustrations of the sensor locations for the adult side impact dummies, BIOSID, EUROSID 1 and SID.

6.2.1 Accelerometers

Linear accelerometers are normally located at the center of gravity (CG) of the head, thorax and pelvis to measure accelerations in each of the orthogonal axes. For some dummy types and/or applications, linear accelerometers are required on the sternum, ribs and thoracic spine. They may be used to measure the acceleration of any body segment. Care should be exercised to ensure that the mass of the accelerometer does not influence the response of the segment to which it is attached and that it maintains the segmental mass within the tolerance limits specified.

The linear accelerations measured at the CG location of the various body segments are combined vectorially to determine the "resultant acceleration" of the body segment. The resultant acceleration is then used to calculate and/or determine compliance with the US Federal Motor Vehicle Safety Standard (FMVSS) 208, Occupant Crash Protection [6.15] and US Federal Aviation Regulations (FAR) Parts 23 and 25 [6.16 & 6.17] and Economic Commission of Europe (ECE) Regulation 95, Uniform Provisions Concerning the Approval of Vehicles with Regard to the Protection of the Occupants in the Event of a Lateral Collision [6.18]. Linear accelerations measured at the lower spine (T12), pelvic CG and upper and lower rib locations are used to determine compliance to FMVSS 214, Side Impact Protection [6.19].

The ADAM, developed by the USAF for escape system evaluation, also utilizes linear accelerometers at the CG of the head, thorax and pelvis to measure accelerations in each of the orthogonal axes.

Linear accelerometers are sometimes used to determine the angular acceleration of a body segment. By

installing an array of accelerometers at locations which are accurately defined in terms of the dimensions relative to each other, the angular acceleration of the body segment may be calculated. More recently, sensors have been developed to provide a direct measurement of angular acceleration. They are primarily used in the head and thorax; however, they may be interfaced to other body segments as well.

6.2.2 Load Cells

Single and multi-channel load cells have been developed to measure the forces and moments (torque) applied to the body components of the dummy during an actual or simulated crash environment. The more recently developed dummies, such as the ADAM, Hybrid III family, BIOSID and EUROSID 1 utilize load cells which were designed at the time the dummies were being developed. Load cells have been retrofitted into some of the older dummies, such as the Hybrid II 50th-percentile, adult male dummy which is still used by the aerospace industry. Load cells are typically located from the head to the feet of the dummy.

The forces measured by load cells located at the lumbar spine and in each lower femur are required for compliance to the FAR. The measurement of femur forces is the only requirement for compliance to the FMVSS. Load cells are required for the calibration of some of the dummy body components such as the neck and knees.

6.2.3 Displacement/Position Sensors

Linear and rotary potentiometers are normally used for measuring the displacement of the body components such as the ribs. The Hybrid III family of dummies has a rotary potentiometer mounted to the front of the thoracic spine with the input shaft driven by an arm attached to the sternum to measure the sternum-to-spine displacement. Linear and/or rotary potentiometers are used to measure the lateral rib(s)-to-spine displacement and the tibia-to-femur displacement.

The ADAM utilizes rotary potentiometers at several body segment joints to determine the position of the body segments during the testing of escape systems. When using the Hybrid III 50th-percentile dummy for compliance to the FMVSS 208, the sternum-to-thoracic spine displacement is a requirement for determining compliance with the regulation.

String potentiometer displacement sensors incorporate a rotary potentiometer within a housing and utilize a small diameter, flexible cable to drive the input shaft. The housing contains a spring which pre-loads the cable tension to a specified force according to the application required. Various pre-load tensions can be specified from the manufacturer. Six (6) string potentiometers are used to measure the lateral rib displacements in the BIOSID.

An array of up to eight (8) units has been installed in a prototype advanced dummy thorax to determine the position of the sternum throughout the crash event. A very small version has been used in the knee of the Hybrid III 50th-percentile dummy to measure the tibia-to-knee displacement.

The user is cautioned to ensure that the displacement sensor has the frequency response characteristics for the application as well as the ability to make the measurement without discontinuities in the signal.

6.3 DATA ACQUISITION SYSTEMS

Data acquisition systems for acquiring test data from the dummies vary widely: off-board the sled or test vehicle, on-board the sled or test vehicle and on-board the dummy.

Some systems utilize telemetry to transmit the data from the dummy/test vehicle to the recording equipment; however, this method is not normally used in automotive crash testing and/or sled simulation. The use of cabling, junction boxes and/or umbilical cables from the transducers to the recording equipment is the more common method for acquiring the test data.

6.3.1 Off-board Systems

Many data acquisition systems consist of laboratory equipment which is too large and/or is not suitable for using directly on-board the dummy, test sled and/or vehicle in a crash environment. These systems require the transducer cables to be connected through junction boxes and/or umbilical cables to the recording equipment which is sometimes located 100 to 300 meters from the test sled or test vehicle. The umbilical cables are dragged by the test sled or vehicle during the test. Some systems multiplex the analog data channels and transmit them, off-board, to the recording equipment via an umbilical cable. Multiplexing

Table 6-2
Adult Escape System and Frontal Impact Dummy Instrumentation

Sensor Location/ Measurement/Channels	ADAM	HYBRID II			HYBRID III		
		50th Male	Large Male	Small Female	50th Male	Large Male	Small Female
Head/Acceleration (CG)/3 channels (ch)	x	x	x	x	x	x	x
Head/Angular Accel./Calculation/12 ch.					x		
Head/Angular Rate Accel./3 ch.	x	x	x	x	x	x	x
Head-Neck Interface/Forces & Moments/3 ch.					x	x	x
Head-Neck Interface/Forces & Moments/6 ch.	x				x	x	x
Neck-Thorax Interface/Forces & Moments/5 ch.							x
Neck-Thorax Interface/Forces & Moments/6 ch.					x	x	
Shoulder/Position/3 ch. ea. shoulder	x						
Arm/Position/1 ch. ea. arm	x						
Elbow/Position/1 ch. ea. elbow	x						
Forearm/Position/1 ch. ea. forearm	x						
Thorax/Acceleration (CG)/3 ch.	x	x	x	x	x	x	x
Thorax/Forces & Moments/5 ch.					x	x	x
Thorax/Temperature/1 ch.	x						
Sternum/Displacement/1 ch.					x	x	x
Lumbar Spine/Forces & Moments/3 ch.					x	x	
Lumbar Spine/Forces & Moments/5 ch.							x
Lumbar Spine/Forces & Moments/6 ch.	x	x					
Lumbar Spine/Position/1 ch.	x						
Pelvis/Acceleration (CG)/3 ch.	x	x	x	x	x	x	x
Pelvis/Lap Belt Position/6 ch.					x		
Pelvis/Force & Moment/2 ch. ea. iliac							x
Hip/Position/3 ch. ea. hip	x						
Upper Femur/Forces & Moments/6 ch. ea. femur					x	x	
Lower Femur/Forces & Moments/6 ch. ea. femur		x	x	x	x	x	x
Lower Femur/Force/1 ch. ea. femur		x	x	x	x	x	x
Knee/Position/2 ch. ea. knee	x						
Knee-Tibia/Displacement/1 ch. ea. knee					x	x	x
Knee-Clevis/Force/2 ch. ea. knee					x	x	x
Upper Tibia/Moments/4 ch. ea. leg					x	x	x
Lower Tibia/Forces & Moments/4 ch. ea. leg					x	x	x
Lower Leg/Torque/2 ch. ea. leg	x						
Foot/Ankle/Toe Forces & Moments/6ch.ea. foot					x		

Table 6-3
Adult Side Impact Dummy Instrumentation

Sensor Location/Measurement/Channels	Side Impact (SID)	BIOSID	EUROSID 1
Head/Acceleration (CG)/3 ch.	x	x	x
Head/Angular Accel./Calculation/12 ch.		x	x
Head/Angular Rate Accel/3 ch.	x	x	x
Head-Neck Interface/Forces & Moments/3 ch.		x	
Head-Neck Interface/Forces & Moments/6 ch.		x	
Neck-Thorax Interface/Forces & Moments/6 ch.		x	x
Upper Spine/Acceleration (T1)/3 ch.	x	x	x
Shoulder/Forces/3 ch.		x	x
Shoulder (rib)/Acceleration/1 ch.		x	
Shoulder (rib)/Displacement/1 ch.		x	
Thorax-Upper Rib Cage/Acceleration/1 ch.	x		
Thorax-Lower Rib Cage/Acceleration/1 ch.	x		
Thorax-Rib Cage/Displacement/1 ch.	x		
Thorax-Ribs/Acceleration/3 ch.		x	x
Thorax-Ribs/Displacement/3 ch.		x	x
Lower Spine/Acceleration (T12)/3 ch.	x	x	x
Abdomen (ribs)/Acceleration/2 ch.		x	
Abdomen (ribs)/Displacement/2 ch.		x	
Abdomen/Force/3 ch.			x
Lumbar Spine/Forces & Moments/5 ch.		x	
Lumbar Spine/Forces & Moments/6 ch.	x	x	
Lumbar Spine/Forces and Moment/3 ch.			x
Pelvis/Acceleration(CG)/3 ch.	x	x	x
Pelvis-Iliac Wing/Force/1 ch. ea. iliac		x	
Pelvis-Sacrum/Force/1 ch.		x	
Pelvis-Pubic/Force/1 ch.		x	x
Pelvis-Ilium/Sacrum Force/1 ch.			x
Pelvis-Angle Transducer/1 ch			x
Femur/Forces & Moments/6 ch. ea. femur		x	x
Knee Clevis/Force/2 ch. ea. knee		x	
Upper Tibia/Moments/2 ch. ea. leg		x	
Lower Tibia/Forces & Moment/3 ch. eà. leg		x	

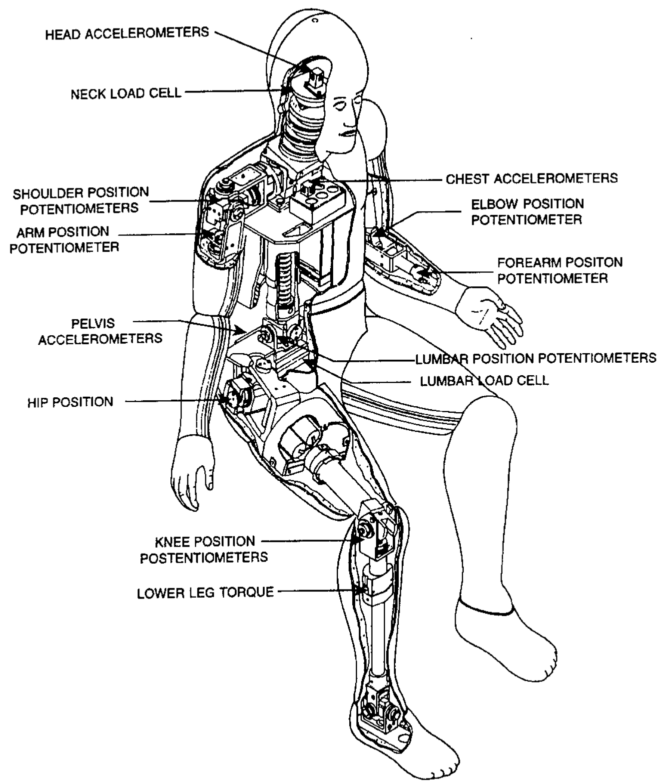

Figure 6-3
ADAM Sensor Locations

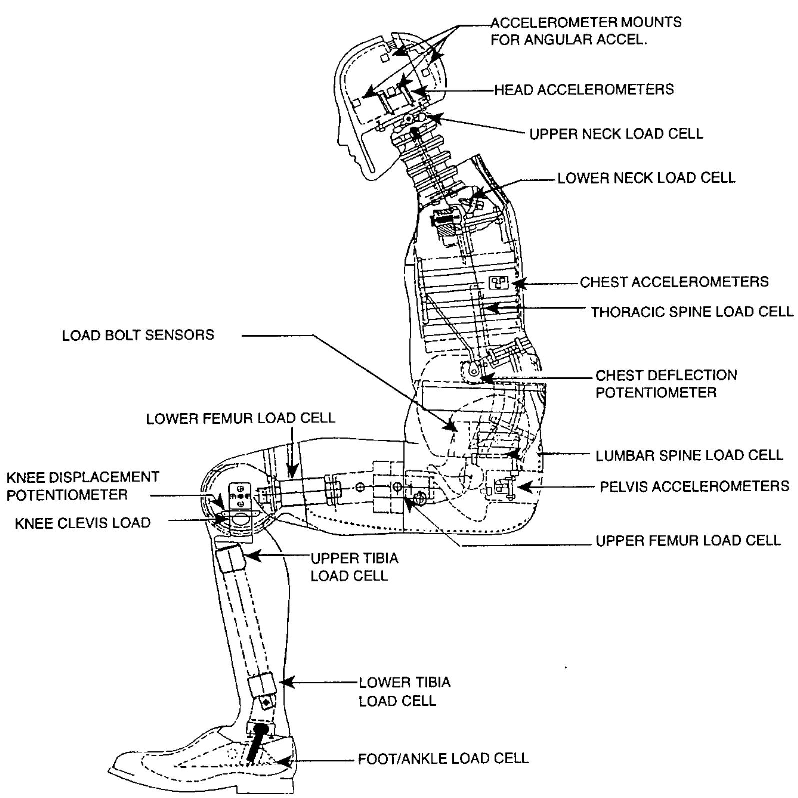

Figure 6-4
Hybrid III Adult Dummy Sensor Locations

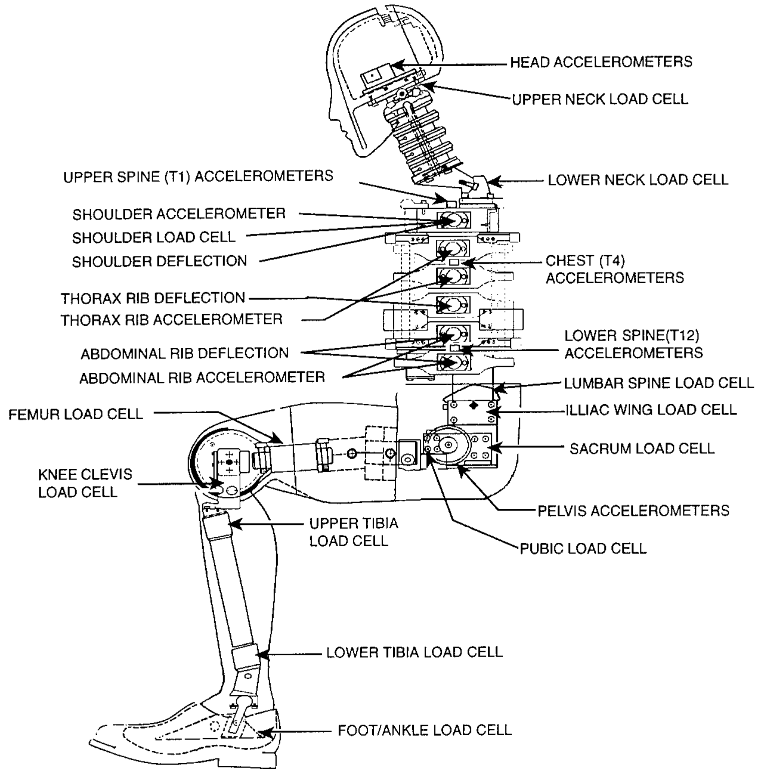

Figure 6-5
BIOSID Sensor Locations

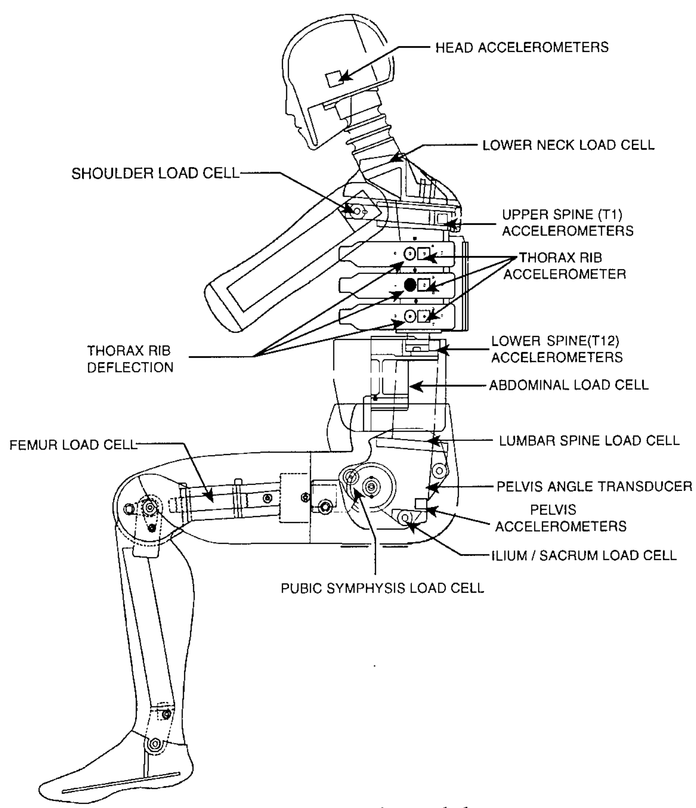

Figure 6-6
EUROSID 1 Sensor Locations

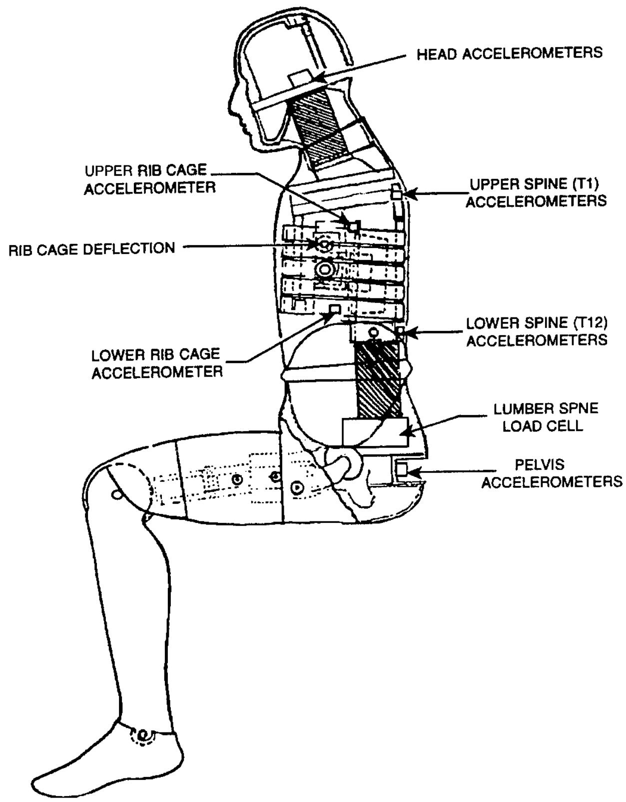

Figure 6-7
Side Impact Dummy (SID) Sensor Locations

reduces the number of cables required; therefore, reducing the size of the umbilical cable.

6.3.2 On-board (Sled or Vehicle) Systems

The most recent on-board systems consist of ruggedized packages that can be installed on-board the sled or test vehicle. All transducers from the ATDs and the structure of the sled or vehicle are connected directly to the system. Signal conditioning, anti-aliasing filtering, digitizing, data scaling and data storage in digital memory having back-up batteries are done within enclosures which are light and small. An umbilical cable is not required. The data are downloaded following the test.

6.3.3 On-board the Dummy Systems

New technology has permitted the recent development of data acquisition systems which are interfaced directly into the dummies. These systems also provide signal conditioning, anti-aliasing filtering, digitizing, data scaling and data storage in digital memory on-board the dummy. The systems are battery operated and have redundant batteries to preserve the memory in case the main battery power is lost during the test. Following the test, the data are downloaded and processed like the other types of data acquisition systems.

The first such system was developed for the ADAM and was integrated into the thorax. A new system was recently developed for the ADAM which provides sixty-four (64) data channels and is also integrated into the thoracic structure [6.20].

A system has recently been developed and integrated into the Hybrid III 50th-percentile dummy [6.21 & 6.22]. The system contains forty-eight (48) data channels and is housed in a modified thoracic spine box designed to maintain the same mass properties (mass, CG and moment of inertia) of the upper torso as those of a standard Hybrid III upper torso.

Chapter 7

New Developments and Special Features

7.1 INTRODUCTION

This chapter addresses recent requirements and capabilities that have resulted from newly identified injury risks, reprioritization of hazard exposures or technological opportunities that may have application to testing, data collection, or response interpretation for aerospace systems. Included are descriptions of upgrades to existing dummies, programs to develop new dummies or components thereof, injury assessment devices, and new methods that are being considered for injury tolerance prediction.

7.2 UPGRADES TO HYBRID III DUMMY FAMILY

The Mechanical Human Simulation Subcommittee of the Society of Automotive Engineers (SAE) Human Biomechanics and Simulation Standards Committee has the responsibility for upgrading the Hybrid III dummy family in response to the needs identified by the US automotive industry and the National Highway Traffic Safety Administration (NHTSA). The following are summaries of recently completed and current SAE projects that relate to upgrading the Hybrid III adult dummy family.

7.2.1 Lap-Belt Submarining Assessment

The crushable abdominal foam insert developed by Rouhana [7.1 & 7.2] to evaluate the injury potential associated with lap-belt submarining (i.e., sliding under the seat belt) has been incorporated into the Hybrid III mid-size male and small female dummies as an optional feature. In addition, the anterior surfaces of the ilia of these two dummies have been modified to accept the anterior-superior iliac spine (ASIS) load transducer developed by Robert A. Denton, Inc (see item **9.2.6.15** in Chapter 9 for Company information) to measure the lap-belt load and its position on the ASIS of the pelvis. For the mid-size male Hybrid III dummy, Robert A. Denton, Inc has developed a load transducer to measure the load applied to the clavicle by the shoulder belt of the automotive three-point belt system.

7.2.2 Hip Modification

At the request of NHTSA and the US automotive industry, an SAE task force was formed to improve the biofidelity of the hip-flexion response of the Hybrid III mid-size male dummy. Based on the results of a human volunteer study of hip flexion, the hip joint was modified to give the desired flexion range and to eliminate the possibility of metal-to-metal contact by installing rubber bump stops within the joint [7.3 to 7.5]. NHTSA is incorporating the modifications into the specification of the Hybrid III dummy given in Subpart E of Part 572 of US Federal Motor Vehicle Safety Standard (FMVSS) 208. Currently, the hip joints of the Hybrid III small female and large male dummies are being upgraded.

7.2.3 Ankle and Foot Modifications

An SAE task force was formed to improve the biofidelity of the ankle joint and foot of the mid-size male Hybrid III dummy. Based on the results of a human volunteer study of foot dorsiflexion, the ankle joint was modified to give the desired range of motion. An internal rubber bump-stop was added to cushion the foot-ankle interaction at the extremes of travel. The foot was modified to give a human-like force-deflection response to loads applied to the heel. NHTSA is incorporating these modifications into FMVSS 208, Part 572, Subpart E.

As a follow-on project, a two-axis ankle joint is being developed for the Hybrid III small female dummy. The purpose of this project is to determine if there is a need to have a more biofidelic and complex ankle joint for assessing a foot/ankle injury. The small female dummy was chosen for this project because of the higher frequency of ankle-foot injuries for the small female driver and because the dummy design is not regulated by FMVSS 208.

7.2.4 Chest Compression Measurements

Both NHTSA and the US automotive industry have expressed an interest in measuring chest compression at more than a single point to obtain a more complete description of thoracic distortion due to shoulder-belt loading. An SAE task force has been formed to evaluate various techniques for making such measurements. The major design challenges are the limited space to install transducers in the chest cavity and the high rate of compression that occurs when the chest is against an air-bag module when the air bag is deployed. String potentiometers, such as those used in the BIOSID and TAD-50M dummies, can be fitted within the chest cavity, but do not respond fast enough to give accurate

compression or rate-of-compression measurements. The SID IIs uses linear potentiometers, but space limitations preclude their use in frontal impact dummies. A number of measurement technologies and linkage systems are being evaluated. To date, none has satisfied the specifications for use in frontal impact dummies. Work is continuing on this project.

7.2.5 Neck Skins

The SAE task force overseeing improvements in the Hybrid III dummy family is evaluating various concepts for covering the neck structures. The purpose of the covering is to provide a more anthropomorphic exterior shape for the neck region to improve air-bag interaction. The major design problems concern the development of a covering that does not change the bending response of the neck, does not short-out the neck load transducers, and is durable. Work is continuing on this project.

7.3 NEW DUMMIES

Several new dummy developmental activities are underway. Two efforts for military applications seek to accommodate a larger flyer population and to improve the biofidelity of the spine. A very small dummy and a very large dummy are being developed by the US military for the Joint Primary Aircraft Training System (JPATS) program and have come to be known as the JPATS dummies. The US Army is developing a new dummy with an improved spine and an on-board data acquisition system that is called the Manikin Integrated Data Acquisition System (MIDAS).

Four dummy developments are underway in the civil sector. There are efforts to:

- improve dummy biofidelity through the Trauma Assessment Device (TAD-50M)
- provide a small size, side impact dummy (SID IIs)
- assess harness interactions with pregnant vehicle occupants
- examine the use of frangible dummy components for response and injury prediction in motorcycle accidents.

The following are discussions of these developmental dummy projects.

7.3.1 JPATS Dummy

The primary JPATS program requirements include testing at body size extremes corresponding to a small female and a large male, having a flexible spine and neck structure, being able to measure neck loads, and testing at up to 475 Knots Equivalent Air Speed (KEAS). The anthropometry for the JPATS dummies is shown in Table 7-1. The existing 5th-percentile Hybrid III automotive crash test dummy and the existing 5th-percentile Aerospace sit-stand dummy were used as a base for the development of the small JPATS dummy (see Table 4-1 for anthropometry). The head chosen is that of the automotive VIP 5th-percentile female modified to accept a neck transducer and a Hybrid III 5th-percentile female neck. The large JPATS is based on the existing Hybrid III 95th-percentile and the Aerospace 95th-percentile male dummies (see Table 4-1 for anthropometry). The head is that of the Hybrid II modified to accept a six-axis neck transducer and the Hybrid III neck. Both JPATS dummies were developed for the USAF by First Technology Safety Systems (FTSS).

7.3.2 MIDAS

Recently, the US Army Aeromedical Research Laboratory (USAARL) developed a prototype manikin called the MIDAS [7.6]. This manikin is a modified Hybrid III dummy with novel spinal column and pelvic design, and built-in signal conditioning and data acquisition electronics. External PC-based software (MIDAS 3.0) is used for control, communication, and post-test downloading and analysis of the data. Plans are underway to re-design the internal battery-based power supply so that field tests can be conducted independently of external connections. Additionally, the internal data acquisition software will be modified to improve serial communication and allow easier modification and retention of default data acquisition parameters.

Table 7-1
General Body Dimensions (m) of JPATS Manikins
Reference Population is Future U.S. Aviator

Dummy Type	Weight (kg)	Stature	Sitting Height	Buttock to Knee Length	Knee Height Sitting	Shoulder Height Sitting	Thumb Tip Reach	Eye Height Sitting	Shoulder Breadth	Chest Depth	Thigh Circum-ference
Small	52.6[a]	1.506	0.828	0.533	0.475	0.549	0.691	0.721	0.381	0.246	0.442
Large	111.1[a]	1.910	0.965	0.706	0.622	0.625	0.917	0.843	0.505	0.292	0.640

a - Weight with on-board data acquisition system

7.3.3 TAD-50M

The TAD-50M (also identified in some references as the Prototype-50M, AATD-50M, or the Hybrid IV) dummy is a research device being developed by NHTSA [7.7 to 7.9] with review by the SAE Enhanced Dummy Task Force. Specific new dummy features include a more human-like rib cage, a flexible thoracic spine, more human-like shoulders with load-bearing clavicles connected to the sternum and improved front-to-back range of motion, a biofidelic frangible abdomen, and an enhanced chest-deflection measurement system. The latter system is capable of monitoring the three-dimensional displacement of the rib cage at the sternum and at the left and right regions of the lower rib cage. The full objectives of this effort and the details of the design are reported by Schneider et al. [7.7]. Constraints on the designs are that the new features must be compatible with the Hybrid III dummy and the anthropometry must be consistent with that specified by Schneider et al. [7.8] and Robbins [7.10]. A comparison of body segmental masses of the TAD-50M with those of the Hybrid III is given in Table 7-2.

Table 7-2
Segmental Masses for Hybrid III and TAD-50M

	Segmental Mass (kg)	
Body Part	Hybrid III	TAD - 50M
Head	4.54	4.54
Neck	1.54	1.54
Thorax	17.23	21.68
Pelvis/ Abdomen	23.09	19.32
Arms	8.54	8.54
Thighs	12.18	12.18
Lower Legs	9.36	9.36
Total	76.48	77.16

7.3.4 SID-IIs Dummy

The SID-IIs is a small [s], second-generation [II], Side Impact Dummy [SID] which has the anthropometry of a 5th-percentile adult female. It has a mass of 43.5 kg, a seated height of 0.790 m, and over 100 available data channels. Based on the height and mass, this dummy is also equivalent to an average 12-13 year old adolescent. The SID-IIs has a special application in evaluating the performance of side impact air bags. The dummy has undergone prototype testing and will shortly be available for independent evaluation. Daniel et al. [7.11] described the technical details of the dummy, its biomechanical design targets and how well it met those targets, its validation requirements, and its instrumentation.

7.3.5 Pregnant Female Crash Dummy

A 5th-percentile female crash test dummy simulating a seven-month pregnant woman is under development by General Motors Corporation (GM), University of Michigan Medical School and FTSS. Based on the standard Hybrid III 5th-percentile female manikin, the pregnant female surrogate has a fetal insert assembly which replaces the chest flesh, skin assembly and the abdominal insert. The abdominal shell is shaped like that of a pregnant female. The fetal body contains triaxial transducers mounted in the head and chest. Load cells measure forces applied to the fetal insert. This dummy will be used to study kinematics in the uterus as the result of vehicular crash trauma, and, possibly, also, in the design of new safety restraint systems.

7.3.6 Motorcycle Dummy

Requirements for the modification of a Hybrid III 50th-percentile male dummy for use in motorcycle crash impact testing have been developed by the International Organization for Standardization (ISO) [7.12]. The primary emphasis in this standard is on the use of frangible legs and an abdominal insert. Other features

include the use of the sit-stand Hybrid III pelvic design, an extension of the head skin to provide helmet compatibility, a neck shroud, and several minor neck modifications.

7.4 HEAD FORMS

Compared to other dummy components, the head form has the most designs. The majority of head forms have been developed for helmet testing. Table 7-3, modified from Newman [7.13], lists the helmet test standards with a description of the head form used. These head forms are primarily rigid shapes used as a mounting block for helmets during testing. Usually they are not attached to a whole body manikin.

7.5 FACIAL DEVELOPMENTS

7.5.1 Surface Tissue Simulants

Soft tissue injuries to the face occur in cars due to contact strikes with the steering wheel, windshield, or other objects. In aircraft, facial injuries can occur when striking objects during survivable crashes, or from glass fragments during ejection or canopy fracture. Standard methods for judging laceration injury have been developed in conjunction with the use of chamois skins and the Gadd Severity Index (GSI) [7.14], the Head Injury Criterion (HIC) [7.15], the Chamois Laceration Scale [7.16], and the Corning Scale [7.17]. All of these methods require skilled subjective interpretations. The Triplex Laceration Index (TLI) [7.18] gives researchers a way to quantitatively assess the severity of lacerations using two layers of chamois and an underlying layer of rubber. The TLI uses a simple mathematical formula to correlate the number, length and depth of cuts in the chamois to a level of laceration severity in the skin. A new method has recently been developed that uses a two-part thermoset silicone mask and an optical scanning technique to quantify the extent of laceration [7.19]. A mask is placed over the dummy's head, it is exposed to an insult, then removed from the head, and placed on a translucent head form. A camera is mounted at a specifically-defined distance from the head form. The camera records the number, length and depth of each laceration as the head is rotated. The data are processed by optical imaging techniques and fed to an analyzing program that determines the severity of the injuries used to calculate the TLI.

7.5.2 Facial Fractures

To assess the likelihood of facial fractures, Melvin et al. [7.20 & 7.21] have developed a deformable facial insert for the Hybrid III dummy which mimics the facial load-time responses that were measured in cadavers. The modified head form is commercially available and has been calibrated to determine the head-to-steering-wheel contact velocity that would produce a prescribed risk of a zygomatic fracture. The facial load for this impact condition is calculated from the measured head accelerations and neck loads using the technique described in SAE J2052 [7.22]. The automotive industry uses this facial fracture assessment for setting deployment levels for air bags. The threshold for deployment of the driver air bag is to assure that the air bag is deployed when the head-to-steering-wheel velocity is predicted to exceed the level for the prescribed risk of a zygomatic fracture.

7.6 NECK DEVELOPMENT

The Hybrid III dummy neck has been accepted as the most biofidelic neck currently available. It is used in the Hybrid III dummies, the Aerospace dummies, and the two ADAMs. It is based on performance requirements for dynamical head-neck behavior in frontal and rear-end impacts as developed by Mertz and Patrick [7.23] and specified in SAE J1460 [7.24]. These performance requirements were derived from volunteer and human cadaver tests.

A number of researchers have analyzed data from human volunteer impact tests conducted at the Naval Biodynamics Laboratory (NBDL) and have suggested changes to the performance requirements developed by Mertz and Patrick. Wismans and Beusenberg [7.25] recommended that rotation about T1 of the neck with respect to the torso should be considered and that a free range of motion in the occipital condylar joint for backward rotation be introduced to provide for initial free head translation as observed in data from volunteer tests and cadavers. Thunnissen and Wismans [7.26] have proposed a set of new performance requirements which take into account both head and neck rotation.

The SAE Human Mechanical Response and Injury Criteria Subcommittee has reviewed the NBDL data, the analysis of Wismans and Beusenberg, and the proposed neck response requirements of Thunnissen and Wismans. They concluded that the proposed neck requirements are not appropriate for an automotive crash test dummy since the NBDL volunteer data were unduly influenced by head instrumentation and by the non-automotive seating posture used in the tests. Based on an analysis of the Mertz-Patrick data, the Subcommittee has added head trajectory requirements to the moment-angle requirements in their update of SAE J1460.

Table 7-3
Helmet Test Standards

Helmet Type	Test Method	Head Form Material	Drop Assembly Mass (kg)	Impact Surface	Impact Energy (Joule)	Impact Sites	Rejection Criteria
Industrial	ANSI Z89.1	Wood or Metal	Missile (3.5)	Steel Hemisphere	55	Top	$F > 4.4$ kN $F_{ave} > 3.7$ kN
Industrial	CSA Z94.1-M1977	Not Specified	Ball (3.5)	Steel Ball	55	Top	$F > 4.4$ kN $F_{ave} > 3.8$ kN
Industrial	BS 5240	Metal or Wood	5.0	Hemisphere	49	Top	$a > 100$ G
Industrial	EN 397	Metal or Wood	5.0	Hemisphere	49	Top	$F > 5$ kN
Firefighters	NFPA	Metal	Head Form (5)	Steel Flat	78	Front, sides, back	$a > 400$ G $a > 200$ G, $t > 3$ ms $a > 150$ G, $t > 5$ ms
						Top	$a > 150$ G
Firefighters			Impactor (3.5)	Steel Hemisphere	55	Top	$F > 4.4$ kN $F_{ave} > 3.7$ kN
Firefighters	prEN 443[1]	?	5.0	Hemisphere	123	Top, 30° front, 30° rear, 30° left and right	$F > 15$ kN
Police Riot	NILECJ 0.0104	Metal	Head Form (5)	Steel Hemisphere	110	Front, sides, back, top	$a > 400$ G $a > 200$ G, $t > 3$ ms $a > 150$ G, $t > 5$ ms
Police Riot	CAN/CSA Z611-M86	ISO Standard Head Form Sizes E, J, M	Head Form (5 + helmet assembly)	Cylindrical Anvil	140 70	All points above test line	$a > 300$ G $a > 200$ G
Ice Hockey	CAN3-Z262.1-M83	Polyurethane Head Form 4 Sizes	Striker (4.5)	Flat Rectangular Birch Block	27 (3 X)	Top, 45° front, side rear 90° side, rear	$F > 8.2$ kN $F_{ave} > 6.7$ kN
Ice Hockey	prEN 967[1]	Metal (EN 960)	3.1 - 6.1	Flat	37[3]	Crown, front, front boss, rear, rear boss, and side	$a > 300$ G and GSI > 1500[5]

Table 7-3 (continued)

Helmet Type	Test Method	Head Form Material	Drop Assembly Mass (kg)	Impact Surface	Impact Energy (Joule)	Impact Sites	Rejection Criteria
Football	NOCSAE	Urethane	Head Form 3 Sizes 3.8, 4.2, 5.3	38 Shore A Flat	25-35 33-47 42-59	Front, side front boss, top rear boss, rear	GSI > 1,500[5]
Crash Helmets	NILECJ 105	Metal	Head Form (5)	Steel Flat	109 (1st) 95 (2nd)	Front, sides, back, top	a > 400 G a > 200 G, t > 3 ms a > 150 G, t > 5 ms
Ballistic Helmets	NILECJ 106	Metal	Head Form (5)	Bullets		Front, sides, back	a > 400 G
Motorcycle, Auto Racing	Snell	Metal or Equivalent	Head Form 3 sizes - B, C, D, (6.5 max)	Steel Flat Hemisphere I Beam, Cylinder	150 (1st) 60 (2nd) 150 150 (1st) 120 (2nd) 100 (3rd)	4 sites above test line	a > 300 G
Motorcycle, Auto Racing	DOT 218	Metal	Head Form 3 Sizes A (3.5), C (5), D (6.1)	Steel Flat Hemisphere	120 (1st) 90 (2nd)	4 sites above test line	a > 400 G a > 200 G, t > 2 ms a > 150 G, t > 4 ms
Motorcycle, Auto Racing	CAN3-D230-M85	Urethane/Epoxy	ISO Head Form Sizes A, E, J, M (5)	Steel Flat Steel Hemicylinder	70 (1st) 140 (2nd) 50 (1st) 100 (2nd)	All points above test line	a > 200 G a > 300 G a > 200 G a > 300 G
Motorcycle, Competition	BS 6658 (A)	Any, but no resonant frequency	5.0	Flat Hemisphere	140 + 76[2] 123 + 63[2]	3 sites above defined test line separated by 1/5 max circumference	a > 300 G
Motorcycle, General Use	BS 6658 (B)	< 3kHz (BS 6489)	5.0	Flat Hemisphere	106 + 53[2] 90 + 46[2]	3 sites above defined test line separated by 1/5 max circumference	a > 300 G

Table 7-3 (continued)

Helmet Type	Test Method	Head Form Material	Drop Assembly Mass (kg)	Impact Surface	Impact Energy (Joule)	Impact Sites	Rejection Criteria
Motorcycle	ECE Reg 22 (03)	Metal (EN 960)	3.1 - 6.1 depending on size	Flat Hemishpere	115[3] 85[3]	Flat, followed by hemishpere at 15mm offset	$a > 300$ G[4] or $a > 150$ G for $t >$ 5ms
Bicycle	ANSI Z90.4	Metal	Head Form (5)	Steel Flat Hemicylinder	54 54	4 sites above test line	$a > 300$G $a > 300$ G
Bicycle	ASTM F1446	Plastic or Metal	ISO Head Form Sizes A, E, J, M (5)	Steel Flat Hemi V-Anvil	90 56		$a > 200$ G, $t > 3$ ms $a > 150$ G, $t > 6$ ms
Bicycle	Snell	Metal	Head Form (6.5 max)	Steel Flat Hemicylinder	136 90	4 sites above test line	$a > 300$ G
Bicycle	CSA D113.2	Urethane/Epoxy	ISO Head Form Sizes A, E, J, M (5)	Steel Flat, Steel Flat Cylinder	56 82 56	6 sites above test line	$a > 200$ G $a > 250$ G $a > 250$ G
Bicycle	BS 6863	BS 6489	5.0	Flat and Kerbstone	52	2 sites with different anvils above defined test line	$a > 300$ G
Equestrian	ASTM F1163	Urethane/Epoxy	ISO Head Form Sizes A, E, J, M (11)	Steel Flat, V-anvil	90 63	4 sites above test line	$a > 300$ G
Equestrian	US Polo Assoc.	Urethane/Epoxy	Head Form 3 Sizes - 3.8, 4.5, 5.3	Steel Hemicylinder 38 Shore A Flat	56-82 56-82 80-95	Front, side, rear top, random	SI > 1,500
Equestrian	prEN 1384[1]	Metal (EN 960)	3.1 - 6.1	Flat	69[3]	2 sites above defined test line separated by at least 150mm	$a > 250$ G or $a > 150$ for $t > 5$ ms
Airborne Sports	prEN 966[1]	Metal (EN 960)	3.1 - 6.1	Flat and Kerbstone	69[3]	2 sites abvove defined test line separated by at least 150mm	$a > 250$ G

Notes:
1. prEN is a European pre-standard, not yet ratified
2. Two impacts per site, the second at half energy of first. Impact energy increased by added mass of helmet
3. For size J headform (4.7 kg). Impact energy increased by added mass of helmet
4. The series 04 amendments will introduce HIC
5. GSI - the Gadd Severity Index [7.42]

7.7 EXTREMITIES

Concerns about the realistic simulation of limb motion and sufficient durability to withstand wind forces during high speed ejections led to two programs to examine the use of composite materials in dummy construction. In a study conducted by VanIngen-Dunn and Arndt [7.27], upper and lower arm and leg segments were constructed for the small ADAM. These were fully compatible with the ADAM design and were fabricated primarily of composite materials with minimal use of metal parts. The design strength was adequate to withstand ejection into a wind stream of 600 KEAS. The mass of the skeletal structure was significantly reduced. This allowed the use of a solid flesh cover which resulted in significantly improved mass-distribution properties, tissue compliance, and energy-absorptive properties that were similar to those of the human. White et al. [7.28] also investigated the use of composites in dummy limbs. A femur and tibia for the Hybrid III dummy were constructed using composite materials. Strain gages and accelerometers were embedded in the femur flesh coverings. Solid Skinflex III coverings (a castable polyurethane elastomer with compliance and density approximately that of human flesh) were fabricated. A piezo-film, tactile-foil pressure-sensor grid was embedded in the covering to measure localized impact forces.

7.8 NEW DEVELOPMENTS IN OCCUPANT PROTECTION PREDICTIONS

The Injury Assessment Reference Values (IARVs) given in Chapter 5 were chosen so that if a dummy's measured responses in a prescribed test did not exceed these values, the associated injuries would be considered as unlikely to occur for that simulated impact condition. A poll was taken of automotive restraint system designers and engineers to determine the level of occupant protection that they desired from the restraint systems that they had designed. The unanimous opinion was that the design level (levels of IARV) should be set so that if they were met, then the associated injuries would be unlikely to occur. There was a difference of opinion as to the meaning of unlikely ranging from 2 to 15% risk of injury. Most thought that a risk of 5% or less was reasonable. Since very little data of injury risk were available, a conservative approach was used to set most of the IARVs of Chapter 5 on analyses based on the biomechanics literature.

7.8.1 Injury Risk Curves and Indices Of Protection

Since the IARVs were formulated for the Hybrid III dummy in 1982, injury risk curves for AIS≥4 brain injury due to forehead impacts and for AIS≥3 thoracic injuries due to shoulder-belt loading have been developed (see Figures 5-9 and 5-10 of Chapter 5). Note that the IARV of 1000 of HIC corresponds to a risk of AIS≥4 brain injury of 16%, and that the IARV of 50 mm for shoulder-belt loading corresponds to a risk of AIS≥3 thoracic injury of 50%. Obviously, these IARVs are set too high to satisfy the desired protection level of 5% or less risk of significant injury.

Work is currently being done to define injury risk curves for other dummy response measurements depicted in Figure 7-1. Statistical techniques such as the Maximum Likelihood Method [7.29 & 7.30], Probit Analysis [7.31 & 7.32], and the Mertz/Weber Technique [7.33 & 7.34] are being used by various investigators [7.34 through 7.36] to analyze available biomechanical data to determine appropriate injury threshold distributions.

Three difficulties are being encountered when analyzing the existing biomechanical data. First, much of the data was obtained from cadaver tests and these results may not be representative of the living human muscular strength. Second, much of the data is statistically censored; that is, a given observation may be above or below the actual failure threshold of the specimen. Analysis of such data requires special treatment [7.34]. Third, there may be insufficient observations to develop a risk curve of the desired precision.

Work is also being done to develop overall indices of restraint performance by combining the individual risks associated with the various dummy measurements as well as for different simulated accident conditions. The most notable example is the five-star rating scheme being used by the New Car Assessment Program (NCAP) of the NHTSA [7.37].

7.8.2 Predictions Of Failure Stresses and Strains

From an academic viewpoint, finite element (FE) models of various body structures are being developed to indicate failure modes based on predictions of internal stresses and strains [7.38 & 7.39].

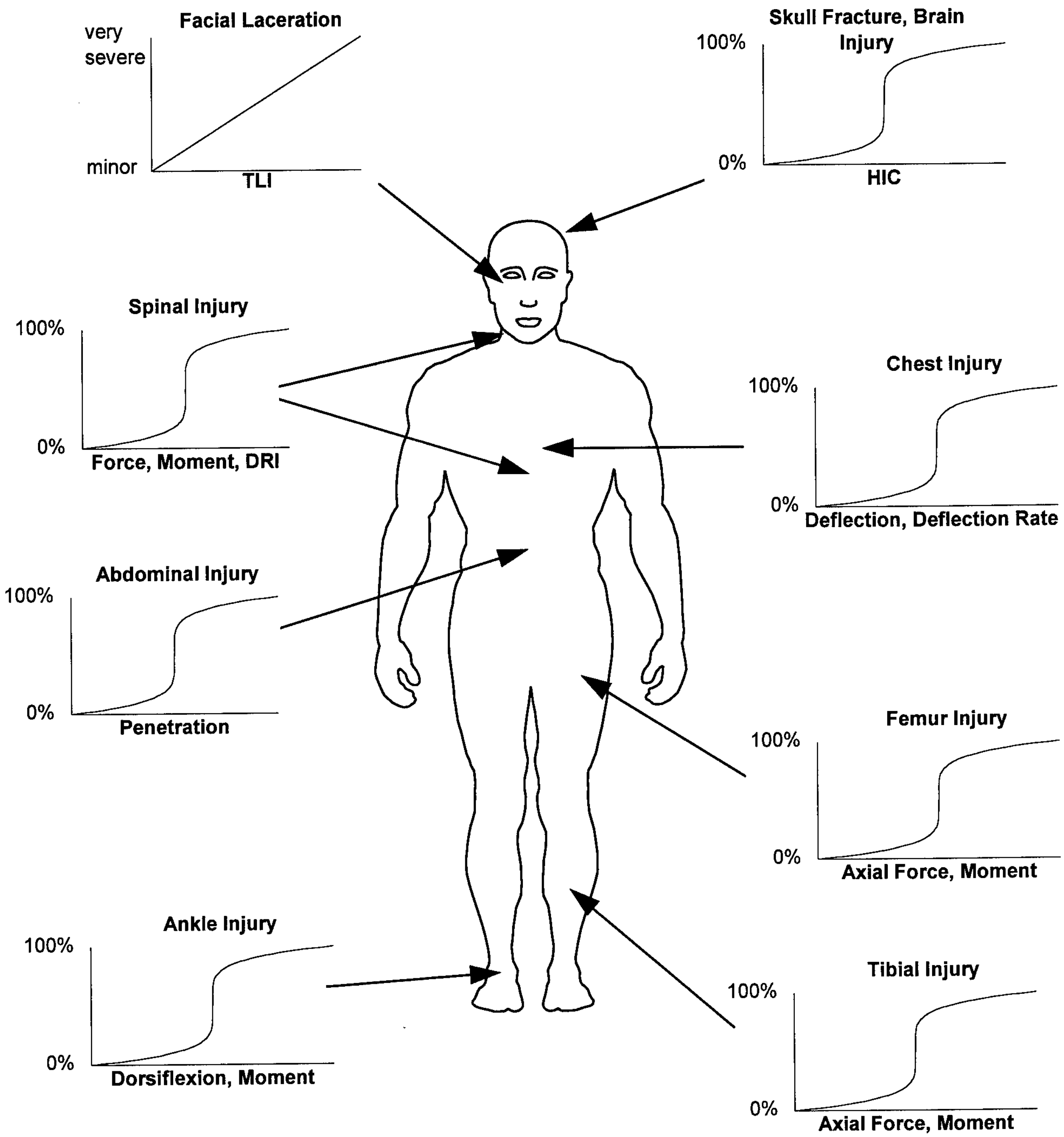

Figure 7-1
Injury Risk Functions for Different Body Regions

7.8.3 Efficacy of Occupant Protection Predictors

The efficacy of any occupant protection predictor needs to be assessed relative to appropriate field accident data. For example, Hackney et al. [7.40] provided an assessment of the efficacy of the NCAP rating scheme by comparing the levels of HIC and chest acceleration measured in NCAP tests of specific vehicles to accident fatality rates for these vehicles. Mertz and Irwin [7.41] noted that there should be a reduction in significant brain injury to occupants in air-bag-equipped vehicles according to the low HIC values that were measured for these cars in FMVSS 208 tests. Air-bag accident data are just becoming available to determine if this prediction is correct

The efficacy of the IARVs for the lower extremities noted in Chapter 5 cannot be assessed yet from field data since few cars have been designed to meet these targets, and the FMVSS 208 test conditions may not be the most appropriate test to evaluate systems designed to mitigate lower extremity injuries. While increasing emphasis is being placed on mitigating lower extremity injuries, it will be a number of years before a sufficient number of cars with improved lower extremity protection are sold and involved in enough accidents to evaluate the efficacy of the current IARVs for lower extremities.

Chapter 8

Data Bases And Analytical Modeling

8.1 INTRODUCTION

When studying the crashworthiness of aircraft systems, investigators use information from actual events, controlled tests, and predictive computer models. Actual events provide the most realistic information, but detailed and quantitative information is rarely available. These conditions force the investigator to use accident statistics on crash or ejection velocity, type of injury, injury severity, and event characteristics to draw conclusions regarding systems effectiveness and safety. Testing can provide much more extensive quantitative information. However, the scope of real world conditions that can be tested is usually limited. Humans, cadavers, and manikins can be used with varying amounts of instrumentation to study the effects of different systems under various exposure conditions. Even in testing, instrumentation is limited and some data cannot be measured without affecting the results. When studying such complex events, the effects of many parameters need to be investigated, but the numerous tests needed can soon become impractical due to the costs involved in testing. Computer modeling can provide a means of alleviating these limitations. Computer simulation can supplement testing by providing additional information not available in tests. Simulations may also be used for parametric studies wherein several scenarios (varying air speed, seat trajectory, crew size and weight, restraint system, etc.) can be analyzed quickly and inexpensively. Parameters and variables that cannot be measured in testing can be predictively calculated, and new system designs may be studied before building prototypes. The limitations in computer modeling depend on how well each mechanism is modeled, the assumptions and idealizations made in developing the model, and the availability and accuracy of input data to characterize the model.

Three basic types of computer model have been developed to represent the human body in automobile accidents, aircraft crashes, and ejections: lumped mass, multi-body, and finite element (FE) models. Lumped mass models typically represent the human body as one or several masses joined to the seat or other structure by a spring-damper system. They can provide basic information regarding seat loading and body acceleration, but are limited in their application. Multi-body models are the most widely used type for simulating occupant dynamics. The human or manikin body is represented as a system of rigid bodies and joints. Often designed specifically for occupant dynamic modeling, multi-body models usually have explicit options for modeling seats, belts, air bags, and other features of an automobile or aircraft. More recently, with the advancements in computer technology, researchers are using FE analysis to model the body. While capable of providing even more detailed information about the stresses within specific body components, FE models require large CPU times. Their reliability and accuracy is still limited since highly detailed structural and material property information is required. As this technology matures, it is expected that standard data bases will be developed and validated, and FE models will be applied more frequently. This chapter focuses on multi-body models because they are the most widely used and standard dummy data sets have been developed for them.

One of the first human-body, gross-motion simulation models was developed 30 years ago by McHenry in the United States. He proposed a two-dimensional seven-segment numerical model to describe the motion of a vehicular occupant in a collision [8.1]. The segments were the head/neck, upper torso, lower torso, thighs, legs, upper arms, and forearms/hands. The results of this model were so encouraging that many, more sophisticated, models have been developed to simulate body motion during automobile accidents, aircraft ejections, and other mechanical force environments [8.2 to 8.6]. Some of the more popular models are: MAthematical DYnamical MOdels (MADYMO) [8.7 to 8.9], developed in the Netherlands; Articulated Total Body (ATB) model [8.10 to 8.13], originally developed as CAL3D and Crash Victim Simulator (CVS) [8.14]; and MVMA-2D [8.15 to 8.17], developed by the US Motor Vehicle Manufacturers Association (MVMA). Each of these models uses some combination of rigid bodies, deformable elements, springs, and dampers to represent the human or manikin body, and sets up and numerically solves the equations of motion for its systems analysis. The applied forces and torques on these components are derived using different routines for contact with exterior surfaces, joint resistance, aerodynamic pressure, gravity, restraint by belt, etc. The ATB and MADYMO programs, the most widely used multi-body models for occupant simulations, are described in more detail below.

8.2 ATB AND MADYMO PROGRAMS

Both the ATB and MADYMO programs were originally developed as linked, rigid-body-dynamics models designed for predicting occupant dynamics during automobile crashes. The ATB model was developed as the CVS for the US National Highway Traffic Safety Administration (NHTSA) during the early 1970s. Later, the Armstrong Laboratory (AL)

took over configuration control of the program and modified it for use in predicting human body dynamics during aircraft ejection, aircraft crashes, automobile accidents, and other hazardous events. Written in FORTRAN 77, the ATB model is a public domain program that runs on a mainframe, workstation, and 386 or higher DOS-based personal computer (PC).

MADYMO was developed by the TNO Crash-Safety Research Centre for the simulation of mechanical systems undergoing large displacements. The program has been designed especially for studying the complex dynamical response of the human body and its environment under the extreme loading conditions of crash situations. MADYMO is marketed by TNO and is supported on most mainframes and workstations.

Both programs have been extensively modified over the years to address specific applications. Aerodynamic force, advanced restraint belt, and other options have been added to the ATB program. This makes it capable of simulating aircraft ejections. An FE method capability has been incorporated into the MADYMO program as depicted in Figure 8-1. This enables MADYMO to simulate the gross motion of systems of bodies connected by complicated kinematical joints, as well as crash behavior of structural components and interactions between bodies and FE structures. Also, MADYMO and ATB have been interfaced with FE-based crash codes.

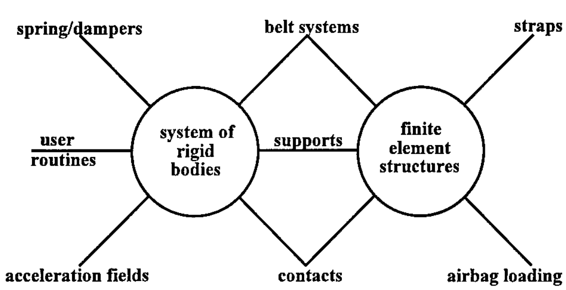

Figure 8-1
MADYMO 3D Structure

The core capability of both models is a three-dimensional, coupled, multi-body dynamical model, in which each body is a segment having constant inertial properties. The bodies can be either rigid or flexible [8.18]. Contact surfaces, defined by ellipsoids, planes, etc., are attached to each segment to provide a means of graphical depiction and a reference for application of forces to the segments. The segments are connected in tree structures with rotational and/or translational joints. Typical human and dummy body data sets consist of thirteen to thirty segments. A fifteen-segment body is shown in Figure 8-2. Forces and torques are applied to the segments based on surface contacts, springs and dampers anchored to the segments, aerodynamic pressure, air-bag contacts, belts attached to the segments, and joint angular resistive and constraint properties. To enable the analysis of muscular activity, mechanisms for representing the active and passive behavior of skeletal muscle have been developed.

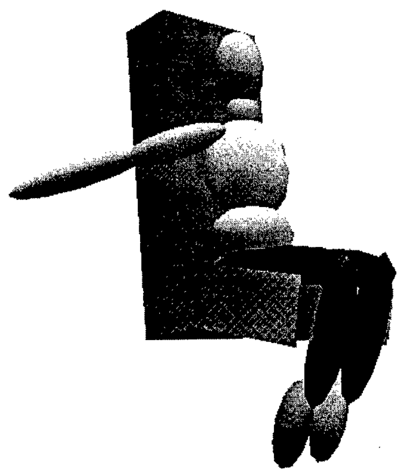

Figure 8-2
ATB Model Ejection Simulation with Fifteen Segment Human Body Model

8.2.1 Input Requirements

The input requirements for any dynamic simulation include a description of the human or dummy body, the environment, the driving motion or force, and the initial conditions.

The body data consist of each body segment's mass, moments of inertia, center-of-mass location, and surface dimension. Also included in the body data are the joints' locations, degrees of freedom, axes of rotation, ranges of motion, and resistive torque properties. A preprocessing program called GEnerator of BOdy Data (GEBOD) uses regression equations based on height and weight to calculate the human body data for adult males, adult females, and children [8.19].

A simulation environment can consist of contact surfaces, belts, air bags, springs and dampers, and other force mechanisms. The seat and cockpit geometries are represented by planes, ellipsoids, hyperellipsoids, cylinders, or arbitrary surfaces. Dimensions for these contact surfaces are typically obtained from design drawings. Throughout the simulation, the programs check for contact between these surfaces and the body

surfaces, and apply contact forces to the body when contact occurs. User-defined material properties for the surfaces are used to calculate the forces. Air bags are defined by their geometry, inflation characteristics, and material properties.

In the ATB model, advanced harness systems and restraint belts are modeled by defining the anchor point locations, the initial trajectory of the belt across the body, the belt material properties, and the body surface properties. The belts are then allowed to slide across and dig into the body surfaces. Wind forces can be applied by either prescribing a pressure-vs.-time history or the wind speed and the properties of air at the simulation's altitude. In the latter case, the program will calculate the dynamic pressure based on the relative velocity between the body or ejection seat and the wind.

In the MADYMO program, the multi-body elements can interact with structures modeled with FEs. Several elemental types may be used including brick, truss, beam and shell elements. Material models include anisotropic elastic, elasto-plastic and Moonley-Rivlin types. Triangular membrane elements with special material models for fabrics have been implemented for the simulation of air-bag and seat-belt dynamics [8.9, 8.20 & 8.21] (Figure 8-3). Point, edge, and surface loads can be applied as can acceleration fields. Input requirements for the FE structures are the nodal coordinates, element definitions, and material properties. Examples of structures that can be modeled with FEs are the seat, seat frame, vehicle interior (padding), vehicle structures, and, if highly detailed simulations are required, certain dummy parts.

Simulations are usually driven by prescribing the motion of one or more vehicles, such as the automobile, aircraft, or ejection seat. This is done by prescribing displacement-, velocity-, or acceleration-vs.-time histories. The motion may be completely three-dimensional combining both linear and angular movements. An applied force, such as the rocket force on an ejection seat, can also be used to drive a simulation. The initial positions and orientations of the body segments are the final inputs required to define the simulation conditions. The models also allow the user to specify the type and frequency of output.

8.2.2 Output Capabilities

The programs have many output options including time histories, tabular data on the status of the simulation at specified time intervals, and data required for depicting the body motion. A wide range of time histories can be generated for each simulation. The time-history output variables include:

- Point positions, velocities, and accelerations
- Segmental orientations, angular velocities, and accelerations
- Joint angles
- Joint forces and torques
- Contact forces and locations
- Belt forces
- Other forces
- Injury criteria
- FE parameters (MADYMO)

Most of these variables can be obtained with respect to any body segment, vehicle, or ground coordinate system. These time histories are in a format that can be read by most commercial spread-sheet or plotting packages.

Both models have graphics post-processors for depicting their results. Most of the figures in this chapter were created by these post-processors.

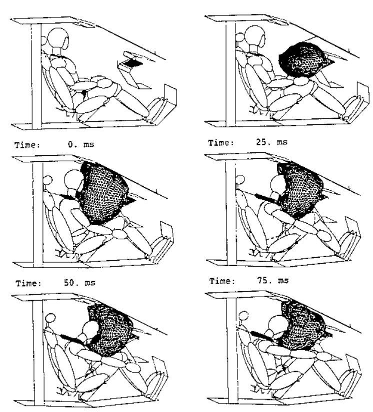

Figure 8-3
Air-Bag Simulation in MADYMO

8.3 CRASH DUMMY MODELS USING RIGID BODIES

Important requirements for the effective use of computer models in the field of crash simulations are that data bases of crash test dummies are available and that they are well-validated. The first step in developing a model of a crash test dummy is the division of the dummy into segments and the specification of the parts that belong to each segment. The segments are selected by dividing the dummy into functional components. Each part of the dummy having significant mass and a flexible connection with other parts is considered a segment. Dummy parts that do not have any relative motion are considered to be a single segment.

Both the ATB and MADYMO models have a variety of joint types for linking these dummy segments. In present dummy designs, usually four types of kinematic connections between segments can be distinguished: pin (revolute) joints, universal (Euler) joints, ball-and-socket joints, and translational joints (Figure 8-4). Often, flexible connections are present in the dummy lumbar spine and neck, which are partly or completely made of rubber. Two ball-and-socket joints, located at the end-plane centers of the structures, are used to represent these structures. The side impact dummy ribs are usually represented by a number of elements [8.18].

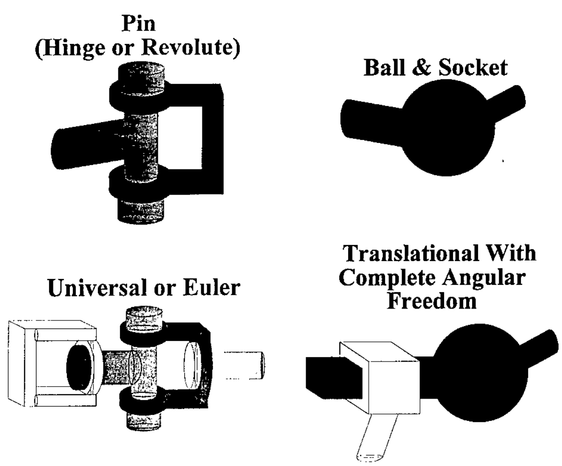

Figure 8-4
Joint Types Used in Dummy Data Bases

Once the linkage structure is determined, the geometric parameters are measured. This includes the joint locations within the individual segments, the joint axes orientations, and the outside surface geometry. Three-dimensional measurements are made on the disassembled dummy. The outside surfaces of the dummy segments are usually represented using ellipsoids. The location and dimensions of these ellipsoids are often estimated from technical drawings. A more accurate method requires a detailed measurement and mathematical representation of the surface geometry from which the optimal ellipsoid parameters can be approximated.

The inertial properties of each segment are also needed. Mass, center-of-mass location, principal moments of inertia, and orientation of the principal axes must be determined for each dummy segment. Landmark positions on the segments are located for defining coordinate systems for relating the joint and center-of-mass locations, and the joint and principal axes orientations. The segmental moments of inertia are determined with a torsional vibration table. The segment is measured in several orientations to obtain the complete inertial tensor.

The stiffness of the connections between the different segments affects the movement and position of the dummy segments in a crash test environment. These joint resistive properties are determined using various static and dynamic test methods. In these tests, the range of motion corresponding to a joint coordinate is determined as a function of the externally applied load. If a joint has more than one degree of freedom, such as a ball-and-socket joint, separate measurements for each degree of freedom are conducted, while keeping the others fixed. Because the actual joint resistance often depends on the value of multiple joint coordinates, large test series may be required. In practice, this dependency on more than one or two degrees of freedom is neglected and the joints are tested with the other degrees of freedom fixed.

The last step in creating a dummy data base is the specification of the surface compliance properties. Static and dynamic measurements with several impactors are made at different locations on the dummy segments. The surface compliance is dependent on the skin covering thickness and density as well as the compliance of the underlying structure. Different impactor surfaces are used to represent appropriate impacting structures. For example, a circular plate is tested against the thorax to represent the hub of a steering wheel. The resulting force deflection properties then are used in the models for expected comparable contacts.

After creating a dummy data base using these measurements, verification simulations are conducted to assure that the input data base properly represents the

dummy. The data base can then be validated by simulating both controlled impactor tests on segments of the assembled dummy and whole-body impact tests at different acceleration levels. The predicted simulation and test results are compared. Good validation studies allow computer modelers to have confidence in using the dummy data base in predictive simulations of events extrapolated from the validated simulations.

8.3.1 Specific Dummy Data Bases

Models of crash test dummies are used to validate the computer models and to supplement tests conducted with the dummies. Model data bases have been developed for many of the dummies described in the earlier chapters.

For example, a cooperative effort to develop and validate modeling data sets for the Hybrid III dummy was conducted in 1987 [8.22 & 8.23]. Supported by the NHTSA, AL measured two Hybrid III dummies to develop an ATB modeling data set. The data were also provided to other organizations for development of MADYMO and other model data bases. Several validation studies were conducted, comparing simulation results with sled test data of a Hybrid III dummy in a frontal impact [8.24 to 8.28].

An ADAM ATB data base was developed by Rizer et al. [8.29]. Based on the structure of ADAM, the model was set up with eighteen segments and seventeen joints. These segments and joints represent the actual rigid bodies and complex articulations found in the large ADAM.

TNO has developed many standard crash dummy data bases for MADYMO. In addition to the Hybrid III family, data bases for the EUROSID 1, SID, BIOSID and others have been developed. Table 8-1 summarizes the status of the availability of the MADYMO data bases.

Table 8-1
MADYMO Dummy Data Bases (1996 Status)

Dummy	Versions	Remarks
Hybrid III 50th Male	2D, 3D (1994)	31 segments (3D) Detailed geometry for interaction with FE air bags and belts Contains special lumbar spine model
Hybrid III 5th Female	3D (1996)	
Hybrid III 95th Male	3D (1996)	
EUROSID 1	3D (1996)	Contains special lumbar spine model
SID	3D (1994)	Contains special lumbar spine model
BIOSID	3D (1996)	Includes FE sections
Hybrid II	2D frontal, 2D lateral, 3D (1992)	
TNO P $^{3}/_{4}$	2D, 3D (1994)	Child dummies
TNO P3	2D, 3D (1996)	
TNO P6	3D (1996)	
European Pedestrian Impactors	3D (1996)	FE model

8.4 MODELING THE HUMAN BODY

A model of the human body is much more difficult to develop than dummy data bases, particularly because of the limitations of the measurement techniques and the lack of reliable joint property and body material data. In spite of these difficulties, it is in modeling the human that computer models can be of most benefit because human volunteers cannot be tested at injurious levels.

The GEBOD program was developed by the AL to generate input data bases of the human body [8.19]. It generates a model for either the ATB or MADYMO programs of fifteen or seventeen segments: head, neck, upper and lower arms, hands, thorax, abdomen, pelvis, upper and lower legs, and feet. Data sets include the mass, principal moments of inertia, orientation of the principal axes, and the ellipsoidal geometry of each body segment. It will also provide the joint types, orientations of the joint axes, joint ranges of motion, and the joint resistive torque properties for use in the ATB model.

GEBOD uses regression equations based on anthropometric surveys [8.30 to 8.32] and stereophotometric data [8.33 & 8.34] to calculate the geometric and mass properties. The regression equations are based on height and/or weight to generate male or female adult data sets, and on age, height, and/or weight to generate child data sets. A user may also input a specific set of up to thirty-five body measurements for the program to use in generating a data set.

Human body models have been used to study the safety performance of restraint systems and body clearances

during ejection for different occupant sizes. Analysis of biomechanical tests and accident reconstruction studies have also used human body simulations successfully. Such simulations generally focus on the global human body dynamics. More detailed models of the human body have been developed to analyze the loading and deformation of the biological tissues, and thereby directly relate external loading to internal injury mechanisms. Two examples of this type of model in MADYMO are the cervical spine model of de Jager (Figure 8-5) and a hybrid multi-body/FE thoracic model (Figure 8-6). The components of these models relate to specific physical structures such as the vertebrae, ribs, and ligaments. Often, this kind of detail allows the study of structural movement and loading, and the investigation of particular injury mechanisms.

8.5 EXAMPLES OF TYPICAL APPLICATIONS

Occupant dynamics in a wide range of aviation environments are being simulated using the ATB and MADYMO programs. The following ATB simulations of an ejection and an aircraft crash, and MADYMO simulations of a space shuttle escape and some aircraft crashes demonstrate how the models can be applied to aviation applications and provide important information to designers and researchers .

8.5.1 Ejection

AL originally began ATB modeling to study human body dynamics during aircraft ejection. Figure 8-7 shows a typical ejection simulation at 437 knots for a 95th-percentile male dummy. In the simulation, ejection seat accelerometer and roll-rate gyro data obtained from a rocket sled test were used to prescribe the seat motion. Other input data included the seat and cockpit dimensions, harness restraint properties, dummy size, and aircraft speed. Using this input, the model calculated the aerodynamic forces on the body based on the changing speed of the seat and applied them to the body as it passed through the plane representing the initial canopy position in the figure. The forces on the body, applied by the harness system and the seat, were also calculated by the model and used to determine the occupant's motion. The figure shows that as the seat begins to move up the rails, the arms and legs begin to fall. At 100 ms, wind forces are being applied to the upper part of the head, which has penetrated the canopy plane. By 200 ms, only the feet remain within the cockpit and are not receiving wind forces. The seat is slightly unstable and begins to rotate at 300 ms. This simulation shows the limb flail that could not be determined from the test. It also provides the forces on the arms when they struck the seat sides and the joint torques due to the aerodynamic forces.

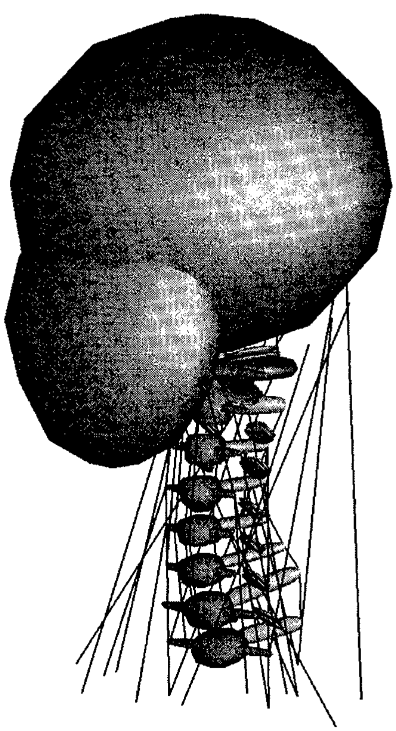

Figure 8-5
MADYMO Multi-body Neck Model

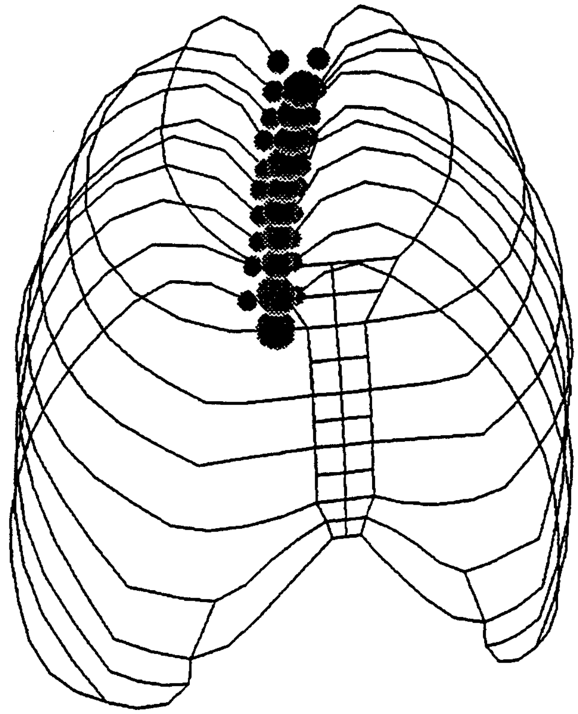

Figure 8-6
MADYMO Multi-body/FE Thoracic Model

This ejection simulation capability has also been used to evaluate body center-of-mass shifts [8.35]. In future ejection seats having their own flight controller to guide the seat, the thruster rockets that propel and steer the seat must compensate for changes in body center of mass due to body motion. Since the center-of-mass locations are not measurable in an ejection test environment, a parametric study was conducted using ejection simulations. The simulations, with varying wind speeds, harness systems, and limb restraints, provided the center-of-mass shifts needed for designing the thruster rockets. Other ejection simulation studies have evaluated the equipment clearances as the crew member leaves the cockpit.

8.5.2 Aircraft Crash

An example of the ATB model used to evaluate the safety of equipment added to crew cockpits relates to the assessment of possible head strikes with a Head-Up Display (HUD) in a cargo plane. During an otherwise survivable crash, crew members without helmets may strike a HUD projector or combiner glass. Before the HUD design was complete, simulations of the occupant dynamics were conducted to investigate this concern. Figure 8-8 depicts the occupant motion from one of these simulations. The three planes in front of the crew member represent the HUD projector and its combiner glass. The simulation shows that in spite of a properly-tightened, harness-belt system, the body deformation and belt slippage allow the body to slide forward considerably during the first 100 ms. In this simulation, the head first strikes the large combiner glass plane and then the two smaller planes of the HUD projector. To evaluate the likelihood of injury, time histories of the contact forces on the head and the head accelerations were generated. Figures 8-9 and 8-10 are plots of these data. At 110 ms, when the head strikes the combiner glass, the contact force in Figure 8-9 results in the first acceleration spike in Figure 8-10. The contact with the two planes representing the HUD projector results in the second spike. Injury criteria based on the head accelerations, such as the Maximal Strain Criterion (MSC) and the Head Injury Criterion (HIC), are used to estimate the severity of injury - see Chapter 5. By running similar simulations with different crash pulses, geometries, padding and harness configurations, possible design options were compared and evaluated before the equipment was built and installed.

8.5.3 Seat and Passenger Response in an Aircraft Crash

On the night of Sunday, 8 January 1989, a Boeing 737-400 crashed on the M1 motorway near Kegworth, England. Of the 126 passengers on board, 79 survived the accident. A comprehensive investigation into the cause and effects of this accident was carried out by a study group of representatives of various organizations. In addition to investigations of structural, medical and survival aspects, computer simulations were used in reconstructing the accident. The overall behavior of the aircraft during the crash was simulated by Cranfield Impact Centre Ltd, UK with the KRASH program. This simulation provided the kinematics of the different aircraft sections [8.36]. The kinematics of the mid-section were used as input for MADYMO, allowing an analysis of seat and passenger behavior during the crash. From this analysis, possible injury mechanisms were identified [8.37 & 8.38]. The influence of different passenger brace positions on the injuries sustained was also studied.

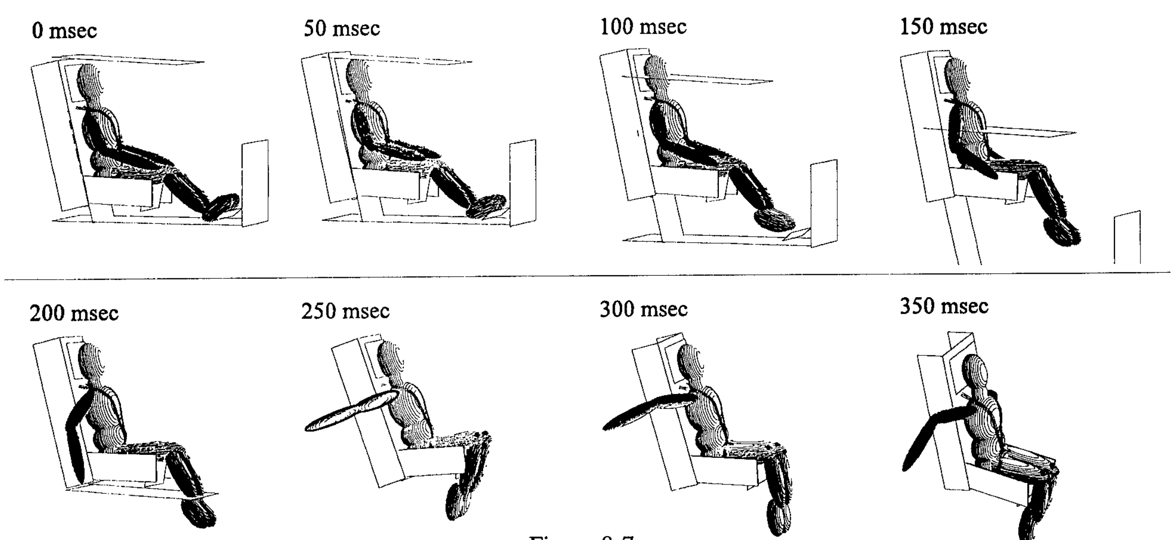

Figure 8-7
Simulation of Human Body Dynamics during a 437 Knot Ejection

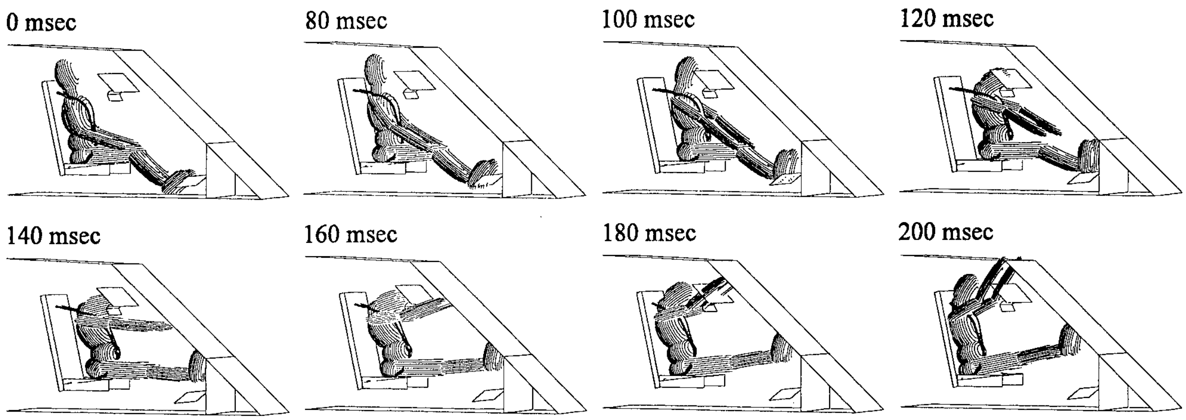

Figure 8-8
Simulated Head Impact with HUD during Aircraft Crash

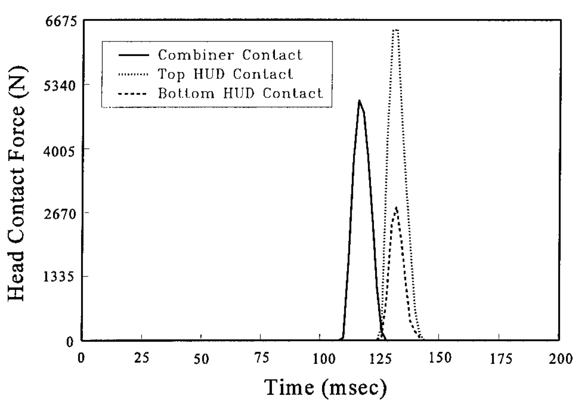

Figure 8-9
Head Contact Forces during Aircraft Crash

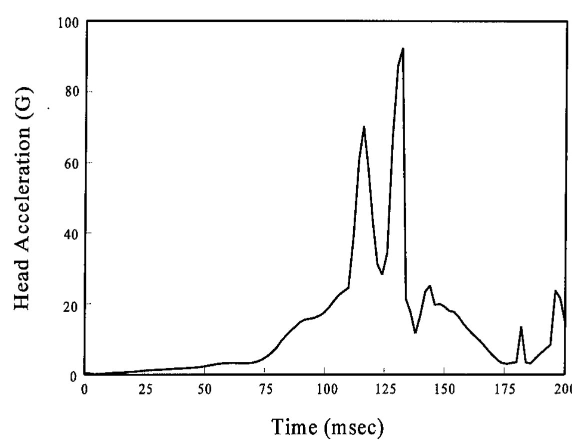

Figure 8-10
Head Resultant Acceleration during Aircraft Crash

8.5.4 European Aircraft Crash-Safety Research

MADYMO is also being used by TNO in its participation in the Brite/EuRam project "Crashworthiness for Commercial Aircraft." This project involves numerical simulations of a complete aircraft, and parts of the fuselage and the interior. To validate the various models and generate input data, experiments are conducted as well. MADYMO is used to simulate passenger behavior during different crash scenarios. The influence of structural design changes to the fuselage on predicted passenger injuries is addressed as well. Two MADYMO models were developed, one employing two triple-seat rows (Figure 8-11) and one involving a cabin attendant seat. Different strategies were followed for obtaining the input data for both models. The seat-row model input was based on a comprehensive series of component tests, whereas the input for the cabin attendant seat model was derived from FE calculations.

8.5.5 Space Shuttle Escape

This MADYMO simulation investigated the in-flight escape of a Space Shuttle crew member [8.39]. One potential method evaluated by National Aeronautics and Space Administration (NASA) to obtain a safe escape from the Space Shuttle uses a tractor-rocket escape system. The astronaut lays backwards on a horizontal ramp with feet placed on a vertical foot plate. A small hatch at the side of the Space Shuttle is available for the escape. The crew-member harness system is connected to the tractor rocket by means of an elastic rope or pendant line. After ejection of the tractor rocket, the pendant line stretches and the astronaut is pulled through the hatch opening. Anthropometry, mass distribution, and joint properties of the astronaut model were based on a 50th-percentile Hybrid II dummy. The aerodynamic forces on the astronaut were modeled as an acceleration field. The rocket propulsive force was estimated. The pendant line was simulated by a spring-damper element with estimated elastic and damping properties. The Space Shuttle itself is represented by contact planes to study the interaction with the astronaut. Figure 8-12 presents the simulated astronaut and rocket locations at several time steps. The developed model allowed the influence of body size, initial position, pendant line stiffness, and pull angle on the astronaut response to be investigated.

8.6 DISCUSSION AND CONCLUSIONS

A general advantage of crash simulation models over experiments with test dummies is that parameters of computer models can be changed easily. Another advantage is that biomechanical research results can be implemented faster in computer models than in crash test dummies because the time-consuming process of dummy design is avoided. In particular, computer crash simulations allow the safety performance of design concepts and changes to be studied efficiently, sometimes without even prototype construction (concept design studies). An important condition for the use of such models is the requirement for well-validated data bases of crash test dummies and humans. Continuous efforts are required to improve the quality of existing data bases to allow their usage to a wider range of applications. Standards for validation procedures and performance criteria are needed to enhance and extend the applicability of computer simulations.

Usually, simulation models of the human body and crash test dummy are based on multi-body methods and, more recently, on FE techniques. A major advantage of the multi-body approach is its capability of efficiently simulating spatial dynamics of mechanical systems with complex kinematical connections, such as those in the human body and in parts of the vehicle structure. The advantage of the FE method is the capability of describing (local) structural deformations and stresses in a realistic way. However, the creation of an FE model is time consuming, realistic material data are limited, and biological tissue responses are often highly non-linear. Furthermore, large computer times are usually required to perform an FE crash simulation, making the method much less attractive for optimization studies involving many design parameters.

Compared to crash-test dummy models, the state of development of real human-body models is still in its infancy. Such models allow the study of body size, posture, and the effects of muscular activity. Model verification studies using human volunteer or human cadaver tests are limited. However, the extensive biomechanical test data available offer promising opportunities in this respect. A major step forward will have been made once mathematical models offer a more realistic representation of the human body than do current crash test dummies. The use of the FE approach, coupled with multi-body techniques is expected to play an important role in improving our understanding of the injury mechanisms involved during crash and other impact events. This understanding can lead to the development of more realistic injury criteria and the availability of more reliable injury tolerance levels. If well-validated mathematical human body models become available, then it is expected that the need for tests with biological surrogates will be reduced.

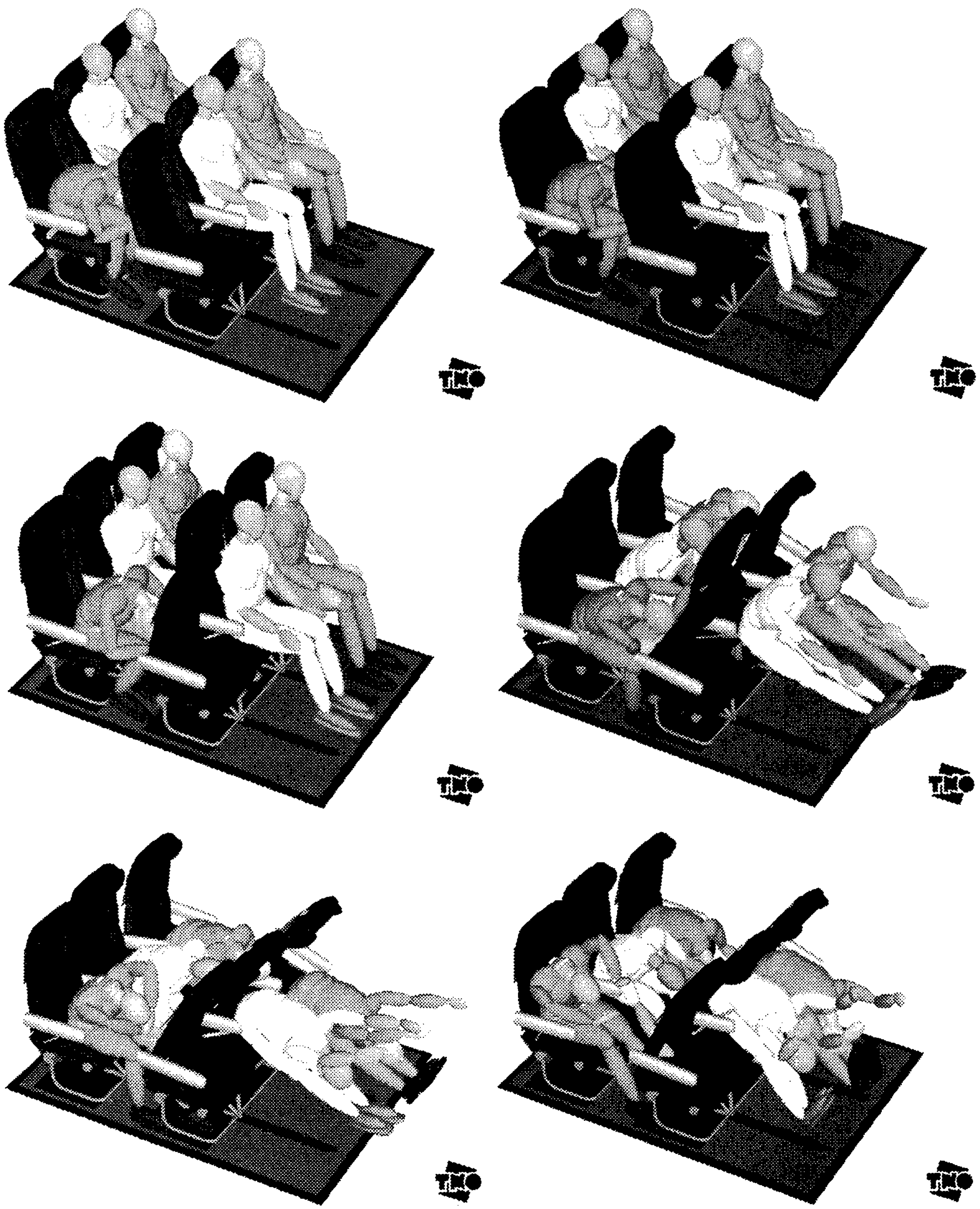

Figure 8-11
MADYMO Simulation of Two Triple-seat Rows

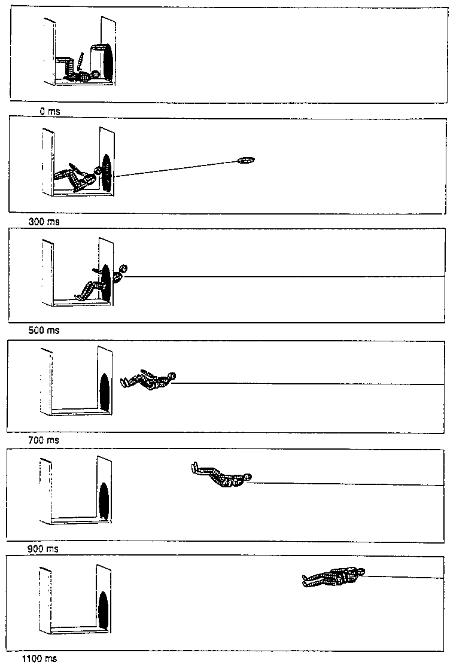

Figure 8-12
Space Shuttle Escape Simulation

In addition to design studies and the analysis of biomechanical tests, the use of computer crash models has been applied in the fields of accident reconstruction and accident litigation. Here, the application of computer models must be handled with great care. While computer simulations often can provide valuable insights into possible occupant dynamics, the results are limited by the validation level of real human body models, the usually large number of unknown accident parameters, and the limited experimental data available for validation of the case under consideration. The development of a code of practice with usage guidelines for models in this field is highly recommended.

Several areas for further development can be identified in the field of computer crash simulations. For crash-test dummy simulations, realistic models for the foam-type structures (skin and damping material) are required. For real human-body models, future developments will include description of the non-linear dynamic behavior of muscles (including reflex activity), the modeling of human joints, and the study of the constitutive equations and parameters for biological materials (e.g., the brain and skin).

Chapter 9

Dummy Users

9.1 BACKGROUND

To obtain details of the range of dummies used in NATO aerospace applications, or available for use in such applications, questionnaires were sent to all known organisations considered to conduct defense-orientated crash or escape system testing. Information requested included contact details; a description of the organization's product and use of dummies; a dummy inventory, with details of special features or modifications; the type of data acquisition system employed and any specialised facilities for calibration.

Finally, details were requested concerning national or international standards used in the application of the dummies to aerospace research and development. Working Group 21 is most appreciative of the many, often very detailed, responses and these are summarised below in a standardised format, and indexed in **9.3.** In general, automobile manufacturers have not been included, though many have facilities to conduct impact tests using dummies, as indicated specifically for Germany.

9.2 USERS: PRODUCT INFORMATION AND DUMMY DETAILS

9.2.1 Canada

9.2.1.1 Centre d'Essais Vehicules Automobiles (CEVA)

100 du Landais Street
Blainville (Québec)
J7C 5C9

Tel: +1(514) 430-7981
Fax: +1(514) 430-2318
Contact: R. Malo, Manager, Collision Laboratory

CEVA conducts collision tests for compliance and research and the evaluation of vehicle dynamic behaviour on test tracks.

ATD Inventory: (5) Hybrid III, 50%ile male, (1) 5%ile female; (5) Hybrid II, 50%ile male, 1 each 5%ile female and 95%ile male; 1 each SID and EUROSID and (2) BIOSID, all 50%ile male; (2) 3 year Hybrid II, one 6 year Hybrid III and one 18 month CRABI. Special features for the Hybrid III 50%ile males include instrumented lower legs, pelvis with load buttons, articulated pelvis and frangible abdomen, upper and lower neck load cells and a 9-accelerometer head cluster.
Data Acquisition: Signal conditioning and FM multiplexing on test vehicle with flying lead to 14 track instrumentation tape recorder. Maximum 84 channel capability. Subsequent digital processing uses a Micro VAX computer.
Standards: Canadian Motor Vehicle Safety Standard (CMVSS) and Federal Motor Vehicle Safety Standard (FMVSS) 208, FMVSS 214 and EU (European Union) Draft Side Impact Standard.
Calibration: Complete Hybrid III and BIOSID facility.

9.2.1.2 Defence and Civil Institute of Environmental Medicine (DCIEM)

1133 Sheppard Ave W, PO Box 2000
North York, ON M3M 3B9

Tel: +1(416) 635-2134
Fax: +1(416) 635-2104
EMail: Don.Day @ dciem.dnd.ca
Contact: D.R. Day, Impact Studies Facility

DCIEM conducts research into the effects of impact on military and civilian restraint systems, and the development of restraint aids, using a HyGe sled.

ATD Inventory: (4) Hybrid II 50%ile male; 1 each Alderson VIP, 5%ile female, 95%ile male; (8) child/infant dummies. The standard instrumentation comprises head, chest and pelvis triax and femur load cells for adult dummies, head and chest triax for the child dummies.
Data Acquisition: Mac II FX computer using Labview Software and National Instruments hardware with 96 channel input capability. 40 sled amplifier channels.
Standards: CMVSS 213, 213.1, 213.2, 213.3
Calibration: Facilities for head, neck, knee, thorax, lumbar spine, abdomen and pelvis.

9.2.2 France

9.2.2.1 Centre d'Essais en Vol (CEV) Essais Sécurité Sauvetage

91228 Bretigny-sur-Orge Cedex

Tel: +33(1) 69 88 20 00
Fax: +33(1) 60 85 03 39
Telex: 604943F
Contact: A. Legendre. SE/EQ/SSP

CEV conducts ejection seat tests on a vertical test tower, parachute tests, and studies on aircraft evacuation, stretchers and aircrew equipment.

ATD Inventory: (10) Alderson type CG, 3/5%ile, 50%ile, 75%ile and 95/98%ile; a 98%ile Aerospace Hybrid III type, a Sereme ONSER, 50%ile and a prototype (Hybrid III based) 50%ile.
Data Acquisition: 14 channels of telemetry (11 at $1kH_z$, 3 at $2kH_z$) plus 1 seat mounted static memory. Under development, specifically for ejection seat testing, is a solid state memory system which will weigh 2kg (16 channels) or 3kg (32 channels).
Standards: Specifications provided by WADC for Alderson type CG series, and Norme Française 1995

9.2.2.2 Centre d'Essais en Vol (CEV) Laboratoire de Medicine Aerospatiale (LAMAS)

CEV/SE/LAMAS
B.P. No 2
F.91228 Bretigny-sur-Orge Cedex

Tel: +33(1) 69 88 23 92
Fax: +33(1) 69 88 27 25
Telex: 604943F
Contact: J.-M. Clere, Head, Biodynamic Division

LAMAS conducts studies on aerospace restraint systems under sustained and impact acceleration. ATDs are used in ejection and crash tests in cooperation with CEV's equipment section or with the Centre d'Essais Aéronautique de Toulouse.

ATD Inventory: One Alderson Hybrid II, 95%ile male.
Data Acquisition: 16 channel instrumentation tape recorder.
Calibration: Carried out as required by UTAC.

9.2.3 Germany

9.2.3.1 Autoliv GmbH

Theodor-Heuss-Strasse 2
D-85221 Dachau
Tel +49-81 31/2 95-226
Fax +49-81 31/2 95-220
Contact: Klaus Röger, Group Leader Test Centre

Autoliv GmbH manufacture complete automotive restraint systems and evaluates their performance using ATDs.
ATD Inventory: (8) Hybrid III 50%ile male and one each 95%ile male and 5% female; (3) Hybrid II 50%ile male. (2) EUROSID 50%ile and (2) SID. The Hybrid IIIs are fully instrumented with head, chest and pelvis triaxial accelerometers, chest deflexion, femur force and G-axis neck transducers. The EUROSIDs have triaxial accelerometers in head, spine and pelvis, 3-axis rib displacement and acceleration, abdomen force, and a single axis pubic symphysis force measurement.
Standards: FMVSS 208 and 214, ECE Regulation 94 (frontal impact) and EC Regulation draft for side impact.
Calibration: Calibration facilities for all dummies are under construction in-house.

9.2.3.2 BMW AG

EG-224, Hautmann
80788 Munchen
Tel: +49 89-382 43866
Fax: +49 89-382 43751
Contact: Edmund Hautmann

BMW AG is an automobile manufacturer with an associated interest in passive safety.

ATD Inventory: Hybrid III and II, US-SID, SID, TNO-P series including 50%ile and 95%ile male, 5%ile female, newborn, 6 and 9 month and 3, 6 and 10 year olds. Instrumentation includes accelerometry, neck load cells, femur and lower leg transducers and chest and rib deflections.
Standards: FMVSS 208, 214, 213 Part 572 and ECE Regulations for car passenger safety.
Calibration: Neck, chest and knee impact pendulums, head drop equipment, lumbar-spine bending apparatus and abdomen compression apparatus.

9.2.3.3 Petri AG

Engineering Centre for Automotive Safety
Hadlichstrasse 19
13187 Berlin

Tel: +49 30/48323-180
Fax: +49 30/48323-181
Contact: Test Engineer Malczyk

Petri AG conducts crash testing for automotive restraint system development, particularly air bags, and are manufacturers of steering wheels, air bags and plastic products.

ATD Inventory: (3) Hybrid III, 50%ile male; 1 each 5% female and 95%ile male Hybrid III; 1 each EUROSID and SID. Standard instrumentation plus neck transducers for the Hybrid IIIs.
Standards: FMVSS 208 and as required by customers.
Calibration: All facilities needed for Hybrid III calibration.

9.2.3.4 Porsche AG

Abt ETM2
Entwicklungszentrum Weissach
Porschestrasse
D-71287 Weissach

Tel: +49 7044 352924

Fax: +49 7044 352900
Contact: Leonhard Ferdinand

Porsche AG use dummies for developing and assessing car passenger crash protection.

ATD Inventory: (7) Hybrid III, 50%ile male; (4) Hybrid II, 50%ile male; (2) Hybrid III, 95%ile male; (2) Hybrid II, 5%ile female; (2) SID 50%ile male; (1) EUROSID, 50%ile male; (4) TNO child dummies, (2) Hybrid II child dummies and (1) air bag child. The Hybrid IIIs are fully instrumented including head, chest and pelvis triaxial accelerometers, 3-axis neck transducer, chest displacement transducer, femur load and knee displacement transducers and optional lower legs fitted with knee force and upper and lower tibia force and moment transducers.
Standards: As required for car crash testing in Europe and US.
Calibration: Complete facility to calibrate all the dummies.

9.2.3.5 TÜV Bayern-Sachsen

Institut für Fahrzeugtechnik, Zentralabteilung
Gesamtfahrzeug Arbeitsbereich Fahrzeugsicherheit
Daimlerstrasse 11
85748 Garching

Tel: +49 89 329557-76
Fax: +49 89 329557-74
Contact: Dipl-Ing. R. Hartmann, Sachbearbeiter

ATD Inventory: (4) Hybrid III, 50%ile male with full instrumentation.
Standards: FMVSS 208

9.2.4 The Netherlands

9.2.4.1 TNO Road-Vehicles Research Institute

PO Box 6033
2600 JA Delft

Tel: +31 15 696336
Fax: +31 15 624321
Contact: Pieter van der Veen, Dummy Engineer

TNO conducts crash safety research for injury prevention.

ATD Inventory: (3) EUROSID, (2) SID, (2) Hybrid II, and (5) Hybrid III, all 50%ile male. One each Hybrid II, 95%ile male and 5%ile female. (4) TNO 10 50%ile male, (2) PO newborn, (2) P 3/4; one P11/2 and two each P3, P6 and P10. All have the standard instrumentation while the EUROSIDs have additional lumbar spine and shoulder force transducers and are modified to provide an indication of pelvic angle.
Standards: Part 572, FMVSS 208 and 214, ECE 94, 95, 44 and 14c and FAR Part 25.
Calibration: Comprehensive test equipment in-house for Part 572 and EUROSID 1 requirements.

9.2.5 United Kingdom

9.2.5.1 Centre for Human Sciences (CHS)

Biomechanics Group
DRA Farnborough
Hants GU14 6SZ

Tel: +44-1252 394093
Fax: +44-1252 377839
Contact: Les Neil

The CHS conducts impact tests on aircraft seats and restraint systems.

ATD Inventory: One each 5%ile female, 50%ile and 95%ile male Hybrid III; an Ogle OPAT 50%ile male and one each 50%ile and 95%ile male Sierra. The Hybrid IIIs are fully instrumented and the OPAT has 6-axis strain gauged clavicles.
Data Acquisition: 16 channel A/D data card in IBM PC using Globalab data software, soon to be replaced by a 16 channel on-board Kayser Threde (KT) K3600 system and DIA-DAGO data software.
Standards: SAE J211. Military standards as required.
Calibration: Hybrid IIIs calibrated in-house to FMVSS 208 with neck flexion/extension, head drop, knee impact and knee slider calibration devices from FTSS, Plymouth, MI, US.

9.2.5.2 Martin-Baker Aircraft Company Limited

Higher Denham, near Uxbridge
Middlesex UB9 5AJ

Tel: +44-1895 832214
Fax: +44-1895 832587
Telex: 23617 Ejects G
Contact: Peter Stevens, Tel +44(0)895 836585
Martin-Baker is involved in the design, testing and manufacture of assisted escape systems for military aircraft, crashworthy seats for aircraft and military vehicles, and associated restraint systems. ATDs are used for in-house testing including ejection seat test rigs, static and truck mounted (up to 70 KIAS) ejection tests, and in ejections from sleds (up to 650 KIAS) and aircraft (up to 450 KIAS).

ATD Inventory: (12) Alderson GARD with anthropometry based on US Naval NAEC-ACEL 533. Sizes include 98%ile, 95%ile, 50%ile, 3/5%ile male,

and a 1%ile female modified from a 3%ile male. The dummies are not specifically instrumented, but are fitted with a telemetry system and head-mounted aerial. (1) Hybrid II, 50%ile male.
Data Acquisition: Interchangeable chest cavity instrumentation packs comprising (2) PCM with 47 channels (including on-board data storage), (1) FM 18 channel and (1) FM 12 channel packs.
Standards: MIL-S-18471(G)AS; MIL-S-9479B (USAF); MIL-E-9426F(AS); MIL-S- 58095A; MIL-S70-810; MIL-D-81514B(AS); AFGS-87235B; ASCC AIR STDS 61/1B and 61/3; ASCC ADV PUBS 61/42A and 61/66A.
Calibration: No formal calibration of the dummies, but dimensions are checked periodically and joint stiffnesses set subjectively (unless a specific value is requested).

9.2.5.3 Millbrook Proving Ground Limited

Millbrook, near Ampthill,
Bedford, MK45 2JQ.

Tel: +44-1525 404242
Fax: +44-1525 403420
Contact: Geraint Williams

Millbrook is primarily concerned with automotive testing, proving and certification using a 12-inch HyGe sled. Work is also conducted on occupant restraint systems and occupant safety for aeronautical, rail and maritime applications.

ATD Inventory: (7) Hybrid III, 50%ile male, (2) Hybrid III 5%ile female; (1) Hybrid III, 95%ile male; (5) Hybrid II, 50%ile male; (2) EUROSID, 50%ile male; (2) 50%ile SID; VIP 95%ile male. 1 each TNO P3/4; TNO P3 and TNO 10. Instrumentation is comprehensive as per the manufacturers' specifications with the Hybrid II modified to give lumbar spine loads.
Data Acquisition: (3) in-house J&R based systems complying to SAE J211 with 16, 64 and 160 channels respectively, and (2) KT systems totalling 214 channels.
Standards: Millbrook is BSI registered to BS 5750 Part 2. The Hybrid II & III and SIDs conform to FMVSS 208. The company is CAA approved for aeronautical testing to JAR 25.562 and accepted by Boeing for the testing of seats, fixtures and interior fittings.
Calibration: Hybrid III ADTs are currently calibrated to FMVSS 572 Subpart E with Subparts B & F soon to be incorporated.

9.2.5.4 ML Lifeguard Equipment Limited, Life Support Division

292 Leigh Road, Trading Estate,
Slough
Berkshire, SL1 4BQ

Tel: +44-1753 523638
Fax: +44-1753 532444
Contact: Bob Spiller

The company manufacturers life support equipment and conducts air blast and impact trials.

ATD Inventory: 1 each Alderson GARD, 5% and 98%ile male and (1) OGLE Design Rescue Training Dummy, 50%ile male.
Data Acquisition: Triaxial accelerometry is currently recorded using the telemetry system at the Defence Test and Evaluation Organisation, Boscombe Down, though an on-board system is being considered.

9.2.5.5 The Motor Industry Research Association (MIRA)

Watling Street
Nuneaton
Warwickshire CV10 0TU

Tel: +44-1203 348541
Fax: +44-1203 343772
Telex: 311277
Contacts: John Nixon, Higher Project Engineer
Dr Viv Stephens, Impact Simulation

MIRA offers a wide range of services to the motor industry with facilities including a proving ground, safety and crash testing and a HyGe sled.

ATD Inventory: (8) Hybrid III and (10) Hybrid II 50%ile male; 1 each 95%ile male and 5%ile female Hybrid III; (2) EUROSID 1 and (4) SID 50%ile male; (7) TNO child dummies; 1 each 95%ile male and 5%ile female Sierra. All dummies with full manufacturers' instrumentation plus special submarining monitoring for the pelvis; frangible abdomen and lumbar spine load cells. Other measurements include seat belt and seat mounting load cells, a seat mount deformation rig and a head form impactor.
Data Acquisition: PC based systems permit 8 channels at $10kH_z$ for dummy calibration and 200 data channels for impact analysis.
Standards: Instrumentation to SAE J211 and ISO 6847
Calibration: A dedicated laboratory permits calibration of the Hybrid dummies according to FTSS specifications. Certification tests in accordance with Federal Regulations Part 572, Subparts B, E & F. EUROSID procedures are currently defined in the User's Manual, but will be specified later in a European Directive.

9.2.5.6 Transport Research Laboratory (TRL)

Old Wokingham Road
Crowthorne

Berkshire RG11 6AU

Tel: +44-1344 770613
Fax: +44-1344 770356
Contact: Dr B. P. Chinn

TRL is a Government research laboratory and conducts automotive crash testing.

ATD Inventory: (3) Hybrid III 50%ile male; (5) OPAT 50%ile male; (2) EUROSID 50%ile male; one each TAD-5OM, Ogle RESCUE and PO, P3/4 and P6 child dummies; (6) RAE Mannequins 95%ile male; one Hybrid III 50%ile male modified for motorcycle crash testing and (4) pedestrian impact test dummies (6 year male (2), 50%ile male and a Sierra SAMMY). The Hybrid IIIs are fully instrumented while the other dummies have standard triaxial accelerometers, load cells, rib deflection potentiometers and so forth. The motorcycle test dummy has frangible (plastic laminate) strain gauged legs, a 9-axis head accelerometer block and a frangible (foam) abdomen insert plus full neck, chest deflection, and spine, femur, tibia and clavicle load cells.
Data Acquisition: 240-channel KT 3600 on vehicle, 48-channel Prosig DAS on the motorcycle Hybrid III and (3) 8 channel Datalab DL 1200, (2) 16 channel and (2) 24 channel Prosig Conquest laboratory systems.
Standards: Most tests can be performed to the appropriate international standards.
Calibration: Full facilities available for EUROSID calibration but all dummy calibration contracted out.

9.2.6 United States

9.2.6.1 Airdrop Test Flight (ATF), 450 LTS/LGHSP

300 Mojave Blvd, bldg 1600,
Edwards Air Force Base
CA 93524-6325

Tel: +1(805)277-3389
Fax: +1(805)277-5009
Contact: Paul McLard, Chief, ATF

ATF conducts research and development parachute testing with ATDs used to assess all phases from egress to landing, and including man-seat separation in ejection systems.

ATD Inventory: (7) 98%ile male, (1) 95%ile male and (16) 5%ile male Aerospace Test Dummies; (19) 5%ile male TUFF KELLY.
Data Acquisition: 5 channel PCM and 27 channel Data-Pro on-board recorder.
Standards: IRIG

9.2.6.2 Armstrong Laboratory, Escape and Impact Protection Branch (AL/CFBE)

Bldg 824, 2800 Q Street
Wright-Patterson Air Force Base
OH, 45433-7901

Tel: +1(513) 255-3122
Fax: +1(513) 255-2019
EMail: TKNOX@ROBIN.AL.WPAFB.AF.MIL
Contact: Dr Francis S. Knox III, Branch Chief

AL(CFBE) conducts experimental research to define human and ATD responses to impact forces and establishes design, testing and evaluation criteria for crew protection and emergency escape systems.

ATD Inventory: (6) each small and large ADAM; (3) GARD C-5, (3) CG-5, 1 each C-95 and CG 95. One VIP 95%ile male. One Hybrid II 50%ile male, (2) Hybrid III 5%ile male, one each Hybrid III 5%ile female, 50%ile and 95%ile males; (4) Model T Parachute dummies and one each Sierra SAMMY and OPAT 50%ile male.
Data Acquisition: The ADAMs have 80 channel on-board EME Corporation solid state DAS's.
Calibration: In-house calibration of all accelerometers and load cells against reference devices calibrated annually to a NIST standard. Manikin necks are calibrated in-house to the SAE J211 test standard.

9.2.6.3 Army Aviation Applied Technology Directorate (ATCOM)

AMSAT-R-TV
Fort Eustis
VA 23604-5577

Tel: +1(804) 878-2561
Fax: +1(804) 878-3029
EMail: KSMITH @ EUSTIS-AATDS1, ARMY.MIL
Contact: K. F. Smith, Aerospace Engineer

ATCOM use ATDs in crash test projects conducted at the NASA-Langley Impact Dynamics Research Facility.

ATD Inventory: GM Hybrid III, 50%ile male with 6-axis spinal load cell in pelvic cavity.
Data Acquisition: 96 channel track mounted transient digital system based on CAMAC real-time, to IEEE 583.
Standards: SAE J211

9.2.6.4 B/E Aerospace, Seating Products Division

607 Bantam Road
Litchfield, CT 06759
Tel: +1(203) 567-7220

Fax: +1(203) 567-7210
Contact: Edward Morgana, Structural Engineering Supervisor

ATDs are used in product certification of commercial airline seating manufacture.

ATD Inventory: (7) Hybrid II 50%ile male with assorted head accelerometers and femur and lumbar load cells.
Data Acquisition: 64 channel UNIX based H.TMS 6000.
Standards: 49 CFR Part 572, FAA 21, 23, 26 & 27.
Calibration: Facilities for head drop, neck flexion and knee impact.

9.2.6.5 Boeing Commercial Aeroplane Group

PO Box 3707, m/s 74-96
Seattle, WA 98124-2207

Tel: +1(206) 237-6014
Fax: +1(206) 237-6149
Contact: Tom Stafford, Engineer

Boeing use ATDs to assess emergency landing dynamics with special attention to internal aircraft structures and crash survivability.

ATD Inventory: (2) Hybrid II, 50%ile male.
Standards: FAR/JAR 25.562, SAE J211, TSO C127.
Calibration: Through CAMI (FAA).

9.2.6.6 Calspan SRL Corp.

4455 Genesee Str, PO Box 400
Buffalo, NY 14225

Tel: +1(716) 631-6816
Fax: +1(716) 631-6843
Contact: David Roberts, Head, Occupant Protection & Safety Research

Calspan use ATDs to test automotive and aircraft restraint devices.

ATD Inventory: (15) Hybrid II 50 %ile male, (3) 95%ile male and a 5%ile female; (13) Hybrid III 50%ile male, one each 95%ile male and 5%ile female; (2) SID, 50%ile male; (6) 3 year old, (4) 6 year old, (4) infant BB and a newborn ATD. With the exception of the infant BB and newborn, all ATDs have head and chest triaxial accelerometers, The Hybrids and 6 year olds have femur load cells and the Hybrid IIIs have 6-axis neck and chest deflection transducers.
Data Acquisition: An in-house 96 channel DAS.
Standards: US DOT FMVSS for frontal and side impact crashworthiness and child restraint performance, USA FAA TSO standards for aircraft seat testing.
Calibration: In-house facilities to calibrate dummies as specified in US CFR for FMVSS 208, 213 and 214D.

9.2.6.7 FAA Civil Aeromedical Institute (CAMI)

CAMI AAM 631, Box 25082
Oklahoma City, OK 73125

Tel: +1(405) 954-5510
Fax: +1(405) 954-4813
Contact: Van Gowdy, Biodynamics Research Section

CAMI conducts civil aviation related crash injury research and investigation.

ATD Inventory: (3) Hybrid II, 50%ile male; 1 each Hybrid III, 95%ile male and 5%ile female; (2) VIP-95, 1 each CRABI, CAMIX, C6-95, Sierra SAM and VIP-50.
Data Acquisition: 48 channel digital system.
Standards: US CFR Parts 23, 25, 27 and 29; AS 8049.

9.2.6.8 Lockheed Aeronautical Systems Company.

86 S.Cobb Drive,
Marietta, GA 30063.

Tel: +1(404) 494-1949
Fax: +1(404) 494-3434
Contact: Robert Trueman

Lockheed conducts engineering flight testing of aircraft including escape system sled tests with ATDs.

ATD Inventory: None in-house, but uses ATDs and facilities of test tracks at Holloman or China Lake.
Data Acquisition: As in *ATD Inventory* above.
Standards: AFGS 87235 and MIL-S-18471.

9.2.6.9 MGA Research Corporation

5000 Warren Road
Burlington, WI 53015

Tel: +1(414) 763-2705
Fax: +1(414) 763-0934
Contact: David Kosloske, Project Engineer, Dummy Calibration Laboratory.

MGA develops and supplies calibration equipment for Hybrid II, Hybrid III and SID ATDs.

ATD Inventory: (2) Hybrid II 50%ile male; (7) Hybrid III 50%ile male; one each Hybrid III 95%ile male and

5%ile female; (3) SID and a BIOSID and one each Part 572 3 and 6 year old child. All dummies are comprehensively instrumented with accelerometers and neck transducers plus chest displacement, lumbar spine force and movement, 2-axis knee clevis load cell, 2-axis upper tibia and 3-axis lower tibia transducers. Two of the Hybrid III 50%ile male ATDs are modified to give increased leg and ankle motion.
Data Acquisition: Ten IBM compatible computers with a total of 102 channels and resolution of 12 bits, an Intelligent Instrumentation system of 60 channels and 29 channels of backup analogue tape recording.
Standards: Full compliance with NHTSA requirements and SAE J211.
Calibration: Head drop device, neck bending pendulum, thorax and knee impact and abdomen compression machines, lumbar flexion and CG measurement devices, dummy measurement table and PC based data acquisition systems.

9.2.6.10 Naval Air Warfare Center (NAWC), Aircraft Division

PO Box 5152
Warminster, PA 18974
Tel: +1(215) 441-2138
Fax: +1(215) 441-3765
Contact: Glenn Paskoff (Code 4.6.2.1)

NAWC conducts crashworthiness studies and tests ejection seats.

ATD Inventory: One each Hybrid III 95%ile, 50%ile, and 5%ile male and 5%ile female; one each GARD 95%ile, 50%ile and 5%ile male.
Data Acquisition: Honeywell Test Management Systems with up to 64 channels for impact testing and 14 channels for ejection seat testing. A custom-designed DAS developed by Conrad Technologies, Inc. with 64 channels is used for the 5%ile female Hybrid III with a modified pelvis.
Standards: SAE J211, MIL-STD-45662.
Calibration: In-house facilities for load cells, dummy joints and durometer testing of dummy skin.

9.2.6.11. Naval Air Warfare Center (NAWC), Weapons Division

Commander (Code 461000D)
One Administration Circle
China Lake, CA 93555-6001
Tel: +1(619) 927-1337
Fax: +1(619) 927-4464
Contact: Cal Kato, Head, Systems Development Division

The Recovery Systems Department (Code 460000D) uses ATDs to qualify new aircrew emergency escape systems and parachute components.

ATD Inventory: (2) Hybrid II 5%ile male; one GARD 50%ile male; (5) Alderson Model 101 98%ile male and (2) each 5%ile male and 3%ile female. Instrumentation includes triaxial accelerometer, and parachute riser forces.
Data Acquisition: 32 channel PCM telemetry.

9.2.6.12 Naval Biodynamics Laboratory (NBDL)

PO Box 29407
New Orleans LA 70189

Tel: +1(504) 257-3892
Fax: +1(504) 257-5456
Contact: Gil Willems, Head, Technology Department

NBDL conducts biomedical research on the effects of the mechanical forces encounted in navy aircraft and ships. ATDs are used to proof-test equipment and to measure shock propagation during ship-shock trials.

ATD Inventory: One each Hybrid III 5%ile, 50%ile and 95%ile male, with triaxial accelerometer and three MHD angular rate sensors mounted in the head and neck.
Data Acquisition: 16 channel in-house built conditioning, filtering and calibration package with a Data Translation Inc. PC based A/D system (used for smaller ATDs). Ectron Model 4020 signal conditioning, and calibration package, Hewlett-Packard Inc. 6944A multi-programmer data conversion system and 9000/220 data acquisition computer used with large ATD. 64 channel capability, 28 channels with on-board conditioning.
Standards: SAE J211
Calibration: Limited to torquing joints and neck tension cable to desired specifications.

9.2.6.13 Northrop Aircraft

14804 Mansel Ave
Lawndale, CA 90260

Tel: +1(310) 332-1919
Fax: +1(310) 331-1412
Contact: Ed Drumheller, Engineering Specialist

Northrop conducts ejection seat tests on rocket sled tracks at Holloman AFB.

ATD Inventory: Alderson 5%ile and 95%ile males.
Data Acquisition: 24 channel FM/FM
Standards: MIL-STD -846; MIL-S-18471G; MIL-S-9479B; AFGS-87235B.

9.2.6.14 Perceptronics Inc.

21010 Erwin Street
Woodland Hills, CA 91367

Tel: +1(818) 884-3485
Fax: +1(818) 348-0540
E Mail: mrector@perceptronics.com
Contact: Michael A. Rector, Project Manager

Perceptronics produces and supplies LIFEMAN manikin, an ATD designed to measure blunt trauma in the vehicle environment and to assess the injury potential of ballistic fragments.

9.2.6.15 Robert A. Denton, Inc.
1220 West Hamlin Road
Rochester Hills, MI 48309

Tel: +1(810) 656-8802
Fax: +1(810) 656-1345
Contact: James L. Blaker, Director, Customer Services

Robert A. Denton designs and manufactures load cells and data acquisition systems for use on test dummies.

ATD Inventory: (2) Hybrid III 50%ile male modified to carry an on-board Intelligent Dummy Data Acquisition System (IDDAS).
Data Acquisition: 48 channel IDDAS.

9.2.6.16 Simula Government Products Inc.
10016 South 51st Street
Phoenix, AZ 85044-5299

Tel: +1(602) 893-7533
Fax: +1(602) 893-8643
Contact: Christopher A. Bradney, Manager, Test Labs

Simula conducts dynamic testing of military and commercial aircraft crashworthiness seating systems.

ATD Inventory: Hybrid III 95%ile and 50%ile male, and a Hybrid II 50%ile male.
Data Acquisition: 32 channel PC based custom-designed system.
Standards: MIL-S-58095, MIL-S-81771A, MIL-S-85810 and FAR Parts 23, 25, 27 and 29.

9.2.6.17 46th Test Group (TGTPA)
1521 Test Track Road, Bldg 1174 Room 119,
Holloman AFB AZ 88330-7847

Tel: +1(349) 679-2502
Fax: +1(505) 679-2906
Contact: Dee Gragg, Senior Analyst

TGTPA conducts high speed track tests of ejection seats and crew modules.

ATD Inventory: (4) Alderson CG 5%ile and (4) 95% male.
Data Acquisiton: 19 channel FM/FM and 32 channel PCM/FM.
Standards: International Range Instrumentation Group.
Calibration: Laboratory with centrifuge, load machine, pressure console etc.

9.2.6.18 Transportation Research Center Inc. (TRC)
10820 State Route 347
East Liberty,
OH 43319

Tel: +1(513) 666-2011
Fax: +1(513) 666-5707
Contact: Jeffery Sankey, Manager, Project Operations

TRC supports the testing of vehicle accident dynamics and conducts research on compliance safety inpact testing.

ATD Inventory: (8) Hybrid III 50%ile male, one each 5%ile female and 95%ile male; (3) Hybrid II 50%ile male; (2) 50%ile SID; one each 6 month CAMI-II, 3 year 572-3C and 6 year 572-6C. Comprehensive instrumentation includes accelerometry, upper neck load cells, chest displacement, upper femur and lower leg load cells and knee displacement transducers.
Data Acquisition: 96 and 118 channel digital DASs.
Standards: FMVSS 208, 213 & 214; CMVSS 208 & 213, European ADAC and ams offset barrier.
Calibration: In-house facilities to calibrate all dummies specified in FMVSS, CMVSS and EEVC procedures.

9.2.6.19 University of Michigan Transportation Research Institute (UMTRI)
2901 Baxter Road
Ann Arbor
MI 48109-2150

Tel: +1(313) 936-1103
Fax: +1(313) 747-3330
Contact: Lawrence W. Schneider, PhD, Head, Biosciences Division

The Biosciences Division of UMTRI does contract research in impact biomechanics, automotive ergonomics accident investigation and anthropometry. Child dummies are used for the sled testing of automotive seat systems, wheelchairs and various occupant restraint systems.

ATD Inventory: One each Riley Low Birthweight Infant; Baby Anne newborn; Part 572K newborn; ECE newborn (Ogle, TNO P-O); Part 572D, and CRABI 6-month; and Part 572J 9-month (TNO P-3/4). The

CRABI has head and neck triaxial accelerometers and upper and lower neck forces and moments.
Standards: FMVSS 213 and CMVSS 213.
Calibration: Ballistic and linear pendulum to calibrate chest and head responses.

9.2.6.20 University of Virginia, Automobile Safety Laboratory
1011 Linden Avenue
Charlottesville
VA 22902

Tel: +1(804) 296-7288
Fax: +1(804) 296-3453
Contact: Gregory S. Klopp, Laboratory Director

The laboratory conducts automotive crash testing using a deceleration sled.

ATD Inventory: Hybrid III 50%ile male with standard head and thorax accelerometers, femur and leg load cells.
Data Acquisition: 128 channel DSP TRAC-Pand 32 channel Denton IDDAS.
Standards: SAE J211 and CFR Part 572.

9.2.6.21 US Army Aeromedical Research Laboratory (USAARL)
PO Box 620577
Fort Rucker
AL 36362 0577

Tel: +1(334) 255-6892
Fax: +1(334) 255-7798
E Mail: Alem@rucker-emh 2.army.mil
Contact: Nabih Alem, Research Biomedical Engineer

USAARL conducts impact tests on helicopter seats, full scale helicopter crash tests and field tests on mine protection kits.

ATD Inventory: Hybrid II 50%ile male and Hybrid III 50%ile male modified with an Applied Physics spine and pelvis to permit twisting, softer bending and greater axial compression and a Hybrid II head to afford better helmet retention. The ATDs have full accelerometry, neck and lumbar load cells with additional accelerometry and a 6-axis pelvis load cell in the modified Hybrid III. An additional Hybrid II head on Hybrid III neck is used to test helmet mounted devices using an 8 channel Teac recording system and high speed video photogrammetry.
Data Acquisition: 18 channels hard wired for the Hybrid II, 24 or 48 channels on-board DAS in the pelvis of the Hybrid III.
Standards: SAE J211.

9.2.6.22 Vought Aircraft Company
Mail Stop 220-J9
PO Box 655907
Dallas, TX 75265-5907

Tel: +1(214) 266-3278
Fax: +1(214) 266-5978
Contact: Kenneth Webman, Manager, JPATS Program

Vought Aircraft Co use ATDs to verify ejection seat performance, ejection envelopes, canopy fracturing systems and personnel safety.

ATD Inventory: (2) Sierra 95%ile male; (2) 5%ile and one 95%ile Alderson Lab Model CG (used in A-7K program); 2 each 95%ile male and <5%ile female based on Hybrid III parts and CG-3 anthropomorphic manikin (for use on JPATS program).
Data Acquisition: The new dummies have 7 channel telemetry systems with three rate gyros, three accelerometers and a harness load transducer and will make use of Holloman AFB test track facilities.
Calibration: In-house facilities for all transducer calibration.

9.2.6.23 Wayne State University
818 W. Hancock
Detroit, MI 48202

Tel: +1(313) 577-8324
Fax: +1(313) 577-8333
E Mail: dupont @ rrb.eng.wayne,edu
Contact: Frank Dupont, Manager

Wayne State undertakes crashworthiness research on behalf of the US Government and automotive industry.

ATD Inventory: (2) Hybrid III 50%ile and one 95%ile males.
Data Acquisition: A 48 channel Denton IDDAS.
Standards: FMVSS 208, 214 and 211.
Calibration: By dummy manufacturer.

9.2.6.24 Weber Aircraft Inc
2000 Weber Drive,
Gainesville, TX 76240

Tel: +1(817) 668-8541
Fax: +1(817) 668-8549
Contact: Vahe Bilezikjian, Director of Engineering

Weber Aircraft tests and certifies transport aircraft passenger seating.

ATD Inventory: (5) Hybrid II, 50%ile male, currently on order for a new in-house test facility. ATDs have spinal compression load cells to SAE AS 8049.
Standards: 49CFR Part 572

9.2.6.25 Wichita State University, National Institute for Aviation Research (NIAR)

1845 Fairmount,
Wichita, Kansas 67260-0093

Tel: +1(316) 689-3678
Fax: +1(316) 689-3175
Contact: Joseph A. Mitchell, Director, Impact Dynamics Laboratory

NIAR conducts research, development and dynamic testing of aircraft seats and restraint systems.

ATD Inventory: Hybrid II, 50%ile male.
Data Acquisition: 60 channel DSP Technology Inc System.
Standards: SAE AS 8049; SAE J211; 14 CFR 23.562, 25.562, 27.562 and 29.562.
Calibration: ATD calibration conducted by FTSS, Plymouth, MI, US.

9.3 INDEX OF DUMMY USERS

Organization		Dummy Types H	S	O	Para.
Airdrop Test Flight (ATF), 450 LTS/LGHSP	US	-	-	43	9.2.6.1
Armstrong Laboratory, Escape and Impact Protection Branch (AL/CFBE)	US	6	-	27	9.2.6.2
Army Aviation Applied Technology Directorate (ATCOM)	US	1	-	4	9.2.6.3
Autoliv GmbH	GE	13	4	-	9.2.3.1
B/E Aerospace Seating Products Division	US	7	-	-	9.2.6.4
BMW AG	GE	U	U	U	9.2.3.2
Boeing Commercial Aeroplane Group	US	2	-	-	9.2.6.5
Calspan SRL Corp.	US	34	2	15	9.2.6.6
Centre d'Essais Vehicules Automobiles (CEVA)	CA	14	4	1	9.2.1.1
Centre d'Essais en Vol (CEV)	FR	2	-	11	9.2.2.1
Centre for Human Sciences (CHS)	UK	3	-	3	9.2.5.1
Defence and Civil Institute of Environmental Medicine (DCIEM)	CA	4	-	10	9.2.1.2
FAA Civil Aeromedical Institute (CAMI)	US	5	-	7	9.2.6.7
Laboratoire de Medicine Aerospatial (LAMAS)	FR	1	-	-	9.2.2.2
Lockheed Aeronautical Systems Company	US	-	-	-	9.2.6.8
Martin-Baker Aircraft Company Ltd	UK	1	-	12	9.2.5.2
MGA Research Corporation	US	11	4	2	9.2.6.9
Millbrook Proving Ground Ltd	UK	15	4	4	9.2.5.3
ML Lifeguard Equipment Ltd	UK	-	-	3	9.2.5.4
Motor Industry Research Association (MIRA)	UK	20	6	9	9.2.5.5
Naval Air Warfare Center (NAWC), Aircraft Division	US	3	-	3	9.2.6.10
Naval Air Warfare Center (NAWC), Weapons Division	US	2	-	10	9.2.6.11
Naval Biodynamics Laboratory (NBDL)	US	3	-	-	9.2.6.12
Northrop Aircraft	US	-	-	2	9.2.6.13
Perceptronics Inc	US	-	-	-	9.2.6.14
Petri AG	GE	5	2	-	9.2.3.3
Porsche AG	GE	17	1	7	9.2.3.4
Robert A. Denton Inc	US	2	-	-	9.2.6.15
Simula Government Products Inc	US	3	-	-	9.2.6.16
46th Test Group (TGTPA)	US	-	-	10	9.2.6.17
TNO Road-Vehicles Research Institute	NE	9	5	15	9.2.4.1
Transportation Research Center Inc (TRC)	US	13	2	3	9.2.6.18
Transport Research Laboratory (TRL)	UK	4	2	20	9.2.5.6
TÜV Bayern-Sachsen	GE	4	-	-	9.2.3.5
University of Michigan Transportation Research Inc (UMTRI)	US	-	-	7	9.2.6.19
University of Virginia, Automobile Safety Laboratory	US	1	-	-	9.2.6.20
US Army Aeromedical Research Laboratory (USAARL)	US	2	-	-	9.2.6.21
Vought Aircraft Company	US	-	-	6	9.2.6.22
Wayne State University	US	3	-	-	9.2.6.23
Weber Aircraft Inc	US	5	-	-	9.2.6.24
Wichita State University (NIAR)	US	1	-	-	9.2.6.25

Note:
H Hybrid II or III
S SID, EUROSID
O Other
U Unspecified Number

Chapter 10

Recommendations

10.1 FORWARD

Recommendations resulting from this report are based on the current state of adult dummy technology, a comparison of automotive-versus-aviation application practices, new requirements for systems safety and operational testing, and technological opportunities. The recommendations fall into four distinct categories:

- improved injury assessment capability
- extension of available dummy sizes
- enhanced instrumentation and affordability
- use of analytical models

10.2 IMPROVED INJURY ASSESSMENT CAPABILITY

The aerospace community has traditionally used dummies to test the operation of aircraft systems such as ejection seats, restraints, crew seats, retraction systems, etc. Ejection safety is judged according to injury potential based on seat acceleration, seat stability, restraint system integrity, and success in getting a dummy under a full parachute prior to a ground impact. Recently, measurements of dummy spinal loads, limb displacements and critical limb forces have been used to evaluate escape systems. Other systems testing is primarily directed at determining structural integrity and proper systems functioning. In automotive applications, systems structural integrity and its proper functioning are also of concern, but systems effectiveness testing has been extended to include an injury potential assessment based on measurements made within the dummy. The approach used in the automotive field can be tailored to consider the different exposure conditions and mechanisms of injury that are applicable to aircraft applications. Therefore, it is strongly recommended that such an approach be developed and applied to aircraft systems testing. New measurement and assessment capabilities would also have to be developed. Specific tasks that need to be accomplished would include:

- identification of significant aircraft operational injuries
- definition of mechanisms and quantitative loading relationships for these injuries
- formulation of injury tolerance levels
- improvement of dummy biofidelity and instrumentation capabilities to measure equivalent human body loading

The automotive community has pursued these steps with reasonable success. The main difficulty has been the accumulation of sufficient, reliable human tolerance data. Much of this data base has been obtained gradually from human volunteer experiments at noninjurious levels, cadaver tests, and a large, road-vehicle-accident data base. For aircraft applications, the first two sources are also available, but accident data, especially those with well-defined exposure conditions, are very limited. This is, and will continue to be, a major problem in defining tolerance levels for aircraft-unique injuries. However, there is a technological opportunity available to pursue this goal, resulting directly from the miniaturization and cost reduction inherent in developing modern data acquisition systems. Therefore, it is recommended that suitably-miniaturized, seat-mounted acceleration recorders be developed for mounting on ejection seats and helicopter crashworthy seats. These would be unobtrusive, noninterfering units that could measure the exposure environment experienced by ejecting or crashing crew members, and would provide the data that can be used directly to correlate exposure level to injury severity.

The automotive industry has been very successful in collecting data on accidents and the associative injuries. This has enabled it to develop an extensive accident injury data base, and prioritize efforts to improve safety in the most prevalent events and for the most frequent injuries. Of course, the number of aircraft accidents is considerably smaller. Therefore, cooperation between NATO nations and organizations in compiling accident statistics is essential to obtain enough data to draw significant conclusions. In that regard, AGARD/AMP Working Group 23: Data Collection in Aircraft Accident Investigation, is concerned with accident causative factors in its quest for the development of a suitable aircraft-accident, human-factors data base. It is strongly recommended that Working Group 23 expand its mandate to also include injury type and injury mechanism in its data base. Then, both the seat recorder and the aircraft accident injury data base will provide the much needed information for determining injury tolerance levels and for justifying specific injury mitigation and safety improvement efforts. These will

also provide the information required for correlating measurements in dummies to injury risk.

10.3 EXTENSION OF AVAILABLE DUMMY SIZES

Traditionally, the testing of aircraft systems has been conducted primarily by using large and small male dummies as test devices. Several NATO nations have opened assignments to female participation; in particular, those for combat flight crew. Other NATO nations are heading toward similar policies. Overall, the aerospace community is continually trying to expand the accommodated population for flight and support operations. To properly test systems for accommodation and safety for the entire flight population, dummies representing the full population range, especially the extremes in range, are needed. In particular, one dummy size capable of high-speed ejection testing is missing. A small female manikin, similar to ADAM, with good biofidelity, on-board data acquisition, and high durability is required.

10.4 ENHANCED INSTRUMENTATION AND AFFORDABILITY

A substantial technological capability is available to measure linear accelerations, rotation rates, thoracic deformations, joint motion, and internal loads in the dummy. Where and how these measurements are made can be adjusted for special applications, though for most automotive applications the measurement techniques are standardized. Enhancements in instrumentation that would be beneficial are the development of a low-cost, compact, and reliable angular accelerometer, and a local-impact, surface-force measurement capability. Angular acceleration is useful in performing injury assessments by providing a direct correlate to injury, and as a variable that is required for the Acceleration Exposure Limit Method described in Chapter 5. Local-impact surface force is important in evaluating the potential for injury from strikes for within-aircraft structures or flying objects.

There is an ongoing transition in the technology for data gathering during ejection seat testing that ranges from telemetry to the on-board acquisition of data. This transition is occurring primarily because of advances made in electronics and in miniaturization, and it should be further encouraged. The ADAM on-board data acquisition system has demonstrated the reliability of this approach as well as its cost effectiveness. The recommended approach is towards a fully self-contained dummy having full on-board data acquisition, programmable data channels, and on-board power sources. This provides an independence from other test-site data acquisition capabilities, reduces test-site requirements for personnel, and should be less expensive. It is further recommended that uniform data acquisition and processing standards should be adopted.

While advances in instrumentation and biofidelity continue to be realized, it is important also that dummies remain affordable and that they can be easily maintained. For new dummies to be widely accepted and used, all cost factors involved in their use must be appropriately minimized. These include the initial cost of a new dummy, the ensuing operational and maintenance costs, and any repair and replacement costs.

10.5 ANALYTICAL MODELS

The use of analytical models can both enhance the information available from dummy testing and reduce the need for testing. Such models can help fill test matrix spaces by interpolating and extrapolating response data, and providing dummy response information that had not been measured directly. Various impact and ejection situations can be examined using such models to determine if and how dummy testing should be performed. Also, and perhaps most importantly, analytical models serve as a bridge in correlating dummy response to human response and hence, enhance human safety assessment. For these reasons, it is strongly recommended that computer models be used in conjunction with dummy testing. However, certain practices should be encouraged to maximize the benefits of modeling. The degrees of freedom and response measures included in a model should correspond as closely as possible to those in the real system. Consequently, validation is essential and model validity should be based on its predictive capability. Standardized models should be developed, along with standardized data bases for dummies and humans. Additionally, to encourage the use of models for investigating various impact situations and their validation, it is recommended that validated simulation data bases be developed and made readily available to potential users.

10.6 CONCLUSIONS

The intent of these recommendations is to lay out a path to a standardized, comprehensive and affordable approach to the performance evaluation and safety assessment of aircrew escape and crash protection systems. They emphasize the use of dummies to make

direct injury risk assessments, expanding dummy sizes to reflect the current and anticipated pilot population, suggest the complementary use of analytical models to reduce test requirements, and advocate self-contained dummy designs that are not dependent on test-site capabilities. These recommendations take advantage of the significant advances made by the automotive community in the development of dummy and injury criteria. Moving forward with these recommendations will enable NATO nations to provide less expensive and safer systems for their military personnel.

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14. Abstract

Anthropomorphic dummies for crash and escape system testing have been used by military and civilian agencies for many years to assess, develop and standardize safer occupant restraint systems for land and air vehicles. The automotive industry has spent considerable effort in designing crash test dummies that are biofidelic; i.e., dummies that duplicate the properties of a representative human subject on which injury risk is to be assessed. This advisory report addresses the status and direction of the technology of aircraft ejection and automotive crash test dummies from the point of view of:

- historical review of important dummies developed in NATO;
- human biomechanical response requirements of current adult dummies;
- anthropometry of current adult dummies;
- injury tolerance criteria for impact exposure of these dummies;
- dummy instrumentation and data acquisition systems;
- new developments in dummies;
- mathematical models as human surrogates; and
- dummy users in NATO.

Recommendations include the need for:

- relating aircraft system effectiveness testing to dummy injury criteria;
- full line of dummy sizes to accommodate entire flying population;
- enhanced dummy instrumentation and data acquisition systems;
- affordability of dummy acquisition, use and maintenance; and
- validation and increased use of mathematical models as human surrogates.

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